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Lava tubes and channels of the Earth, Venus, Moon and Mars

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LAVA TUBES AND CHANNELS OF THE EARTH, VENUS, MOON AND MARS

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PUBLICATIONS

Some of the work presented in this thesis has been published in the paper:

"Venus Unveiled : The Magellan Images" **by**

Zealey, W.J., Melville, G.P., and Kreig, M.

Proc. ASA 10, 3 (1993)

and can be found in Appendix C.

ABSTRACT

The Magellan spacecraft was placed into an elliptical orbit about Venus in August 1990; a month later it began regular acquisition of altimetry and synthetic aperture radar (SAR) data. Although Earth based radar has revealed that volcanic activity has occurred on Venus at some time in the past, no fine details, which would now become available, have previously been seen.

Lava channels, collapse craters and especially lava tubes in particular should be able to be seen on the high resolution (120 m) Magellan radar images and can thus be compared with similar structures on the Earth, Moon and Mars and comparisons made.

The study has shown that lava channels certainly exist on Venus but are far larger in dimensions than any known elsewhere in the Solar System. Venusian channels cannot be properly compared to those on the Earth because of their vastly larger scale but making them closer to lunar dimensions. Many collapse features on Venus may be attributed to collapses resulting from the withdrawal of magma below the Venusian surface. Although conditions on Venus such as topography, lava type temperature etc. are very favourable for the formation of lava tubes, evidence for their existence is mostly circumstantial, although very compelling.

CHAPTER 1 THE PROJECT

1.1 Aim

The aim of this project is to identify on Venus a wide sample of certain geological features such as lava channels[1], lava tubes and related collapse craters, to characterise these features, and identify possible underlying causes.

1.2 Method

In order to achieve the aim the following steps were taken:

1. Magellan images were surveyed for the presence of any pit or channel-like structures with particular attention being paid to volcanic areas such as cone fields.

2. Statistical data such as length, width, morphology etc., were collected to characterise the structures.

3. Any possible connection with surrounding features such as faults, craters etc. was evaluated.

4. These Venusian lava structures were compared with those of the Earth, Moon and Mars.

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1. In this thesis a lava channel is loosely referred to as any 'channel' or 'course' on the surface of Venus which facilitates or has facilitated the flow of lava. Lava tunnels below the surface are referred to as lava tubes.

1.3 The Magellan Project

Venus is the Earth's near twin in regard to size, mass and distance from the sun. They were born almost at the same moment, in nearly the same region of space.

The Earth and Venus also formed out of almost identical material and being subject to the same laws of physics, they condensed into nearly spherical bodies in what can be assumed are similar structures. From this similar beginning, however, both planets have evolved separately to now have contrasting surface and atmospheric conditions.

The surface of Venus experiences temperatures of up to 460^0C and a pressure of 92 atmospheres, 97% of which is carbon dioxide (Pinn, 1985). Venus is also permanently shrouded in thick yellow clouds (Photo 1), her face forever hidden from eyes that see in the visible portion of the electromagnetic spectrum. It is therefore unclear whether the crust has evolved in a similar way to the Earths' crust. Fortunately, radio waves a few centimeters long can easily pierce the clouds, permitting earthbound radiotelescopes such as Ariceibo and Goldstone, and U.S. and Soviet space probes to reconstruct a crude picture of the Venusian landscape in early attempts at radar mapping.

In the late 1970's, the U.S. Pioneer Venus spacecraft returned radar soundings from hundreds of orbits around Venus covering 93% of the surface (Pinn, 1985).

In 1983, the Soviet Venera missions obtained 1-2 km resolution images of 25% of the surface. These observations revealed for the first time a surface showing considerable tectonic activity such as folding ridge belts, volcanism and coronae, as well as evidence for large impact craters (Pinn, 1985).

The Magellan spacecraft (Photo 2) was launched from the Kennedy Space Center on May 4, 1989. Mapping began in August, 1990, using a **Synthetic Aperture Radar(SAR)**, (see explanation on the next page and Photo 3). The initial mapping was completed in May, 1991, and a second cycle in January, 1992 (NASA mission data, 1991).

The spacecraft was placed in an elliptical orbit around the planet, with a periapsis latitude of approximately 10 degrees north, a periapsis altitude of 295 km, and a period of 3.263 hours. Apoapsis altitude is approximately 7762 km. The range of latitude covered by the radar is 67 degrees South to 90 degrees North. The range of look angles for the SAR is 13 degrees to 44 degrees from nadir. The SAR data are taken at a data rate of 750 kb/s and are stored in the spacecraft tape recorder. Altimeter and radiometer data are also taken whenever the radar is operating (NASA mission data, 1991).

As the spacecraft moves away from the planet toward apoapsis, the spacecraft reorients the high-gain antenna towards the Earth and the stored data are transmitted to DSN stations on Earth. This data taking- and transmitting- cycle is repeated every orbit revolution (NASA mission data, 1991).

After 243 days the planet is completely mapped except for gaps and the area near the South Pole. On Earth, the SAR, altimeter and radiometer data are processed into images and maps for scientific study (NASA mission data, 1991).

1.3.1 SYNTHETIC APERTURE RADAR (SAR)

The resolution of a single aperture radar system is expressed as a solid angle (θ - radians), and is given by

$$\theta = 1.22\,\lambda / D$$

where λ is the wavelength and D is the diameter of the antenna. At radar wavelengths, this is quite a large value for portable antennae. This means resolution is controlled by the size of the antenna, that is, to improve resolution a larger antenna is needed. Such radar systems are known as real-aperture radar systems.

Clearly, such a system is impractable if high resolution images, such as those of Magellan, are required since it would lead to an unrealistic antenna length. For example, a radar operating at a wavelength of 25 cm, at an altitude of 100 km requiring an azimuth resolution of 100 m would need an antenna 250 m long.

However, there are ingenious ways of avoiding this limitation. More-complex systems use the coherent nature of artificial micro-wave radation to stimulate an extremely long antenna. These systems are called **synthetic-aperture radar (SAR)** systems, and are the only useful means for high-altitude and satellite radar remote sensing.

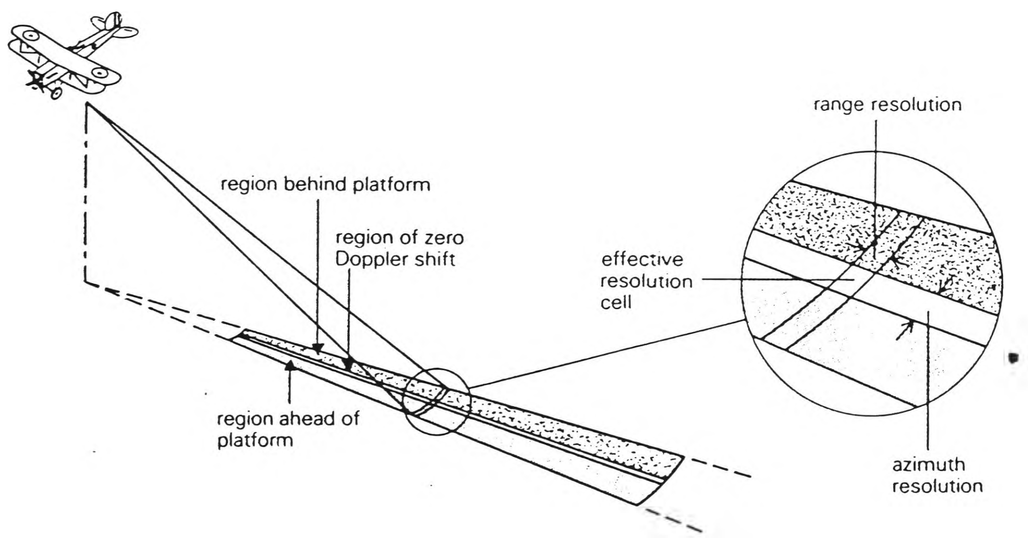
Within the ground area illuminated by the pulsed radar beam (Figure 1 and Photo 3), some parts of the surface are ahead of the platform, some are behind, and only a narrow strip, just as wide as the antenna itself, is in line at any instant. The returns from the areas ahead and behind are subject to a **Doppler shift**, just as the horn of an approaching train would be higher pitched. Although, the shift is very small at satellite speeds, because radar is coherent, these small differences can be detected.

In a SAR system the time, the energy and the frequency of radar returns from the surface are recorded, different frequencies signalling the position of the object responsible relative to the motion of the platform. The frequency is measured by allowing the returns to interfere with a reference signal whose frequency is the same as that of the radar pulse itself (Drury, 1987).

Those frequencies affected by Doppler shift produce interference patterns. A constructive interference produces a high-intensity signal, a destructive interference gives a low-intensity signal. The net result is that the moving real antenna is transformed into a much larger, synthetic antenna, thereby improving the azimuth resolution.

Although the Magellan radar antenna is only 3.7 m in diameter and operates at 12.6 cm wavelength, by utilising an SAR system, slant-range resolution is as low as about 80 m. This means details as small as 120 m across, one tenth the size of those previously detectable, are visible.

FIGURE 1 **THE SAR SYSTEM**



1.3.2 DIFFICULTIES ASSOCIATED WITH RADAR IMAGES

Despite the benefits of radar in imaging it does present problems. Because radar looks sideways, and because radar images represent energy and time, it produces some extraordinary geometric features as well as those resulting from platform instability and planet rotation.

The three most important are listed below :

1) Uncorrected radar images vary in scale along the range. The image is compressed at near range and only approaches true scale at far range. This is explained by Figure 2, and results from the different **incidence angles** of radar wavefronts at different ranges.

2) If the surface has high relief a most strange effect is produced. Because the top of a mountain may be nearer to the platform than its base, and because radar images are time images, the top is sometimes reproduced closer to the platform than the base of an image. The mountain 'leans' toward the platform to give a phenomenon termed **layover** (Figure 3). The layover effect depends partly on the relief, but mainly on the depression angle, being worst for high depression angles and the strongest relief. The effect at its most bizarre can display a mountain overlaying a river.

3) Related to layover is **foreshortening**. This occurs where the surface slope is less steep than that of the radar wavefront. The pulse reaches the base before the top, so that the sloped surface appears shorter on the image than on the ground (Figure 4a). Where the surface is parallel to the wavefront, all points on it are exactly the same slant distance from the platform, so that they all fall together on the image as a single point (Figure 4b).

The best solution to these problems is to make images from such an altitude that only a small range of depression angles covers a very broad swath on the ground. The best images are, thus, from orbit.

NOTE

Perhaps the most obvious feature of radar images of variable relief is their **sidelit** character. Slopes facing the platform are most strongly illuminated and reflect most of the energy back to the antenna, so show up as bright. Slopes facing away receive least energy and appear darker. Where such slopes are steeper than the radar raypaths they are in **radar shadow**, they receive no energy and appear totally black. The farther the range is, the lower the depression angle and the lower the relief needs to be to produce a radar shadow.

FIGURE 2 In a slant-range image the scale downrange increases because the depression angle of spherical wavefronts which meet the surface decrease away from the antenna. The apparent distances between objects and between parts of the same object are measured in time. The time taken to illuminate A is shorter than for B and C. Similarly, it takes longer for a wave to move from B to C than from A to B. The equal distances on the ground increase away from the platform on the slant-range image (Drury, 1987).

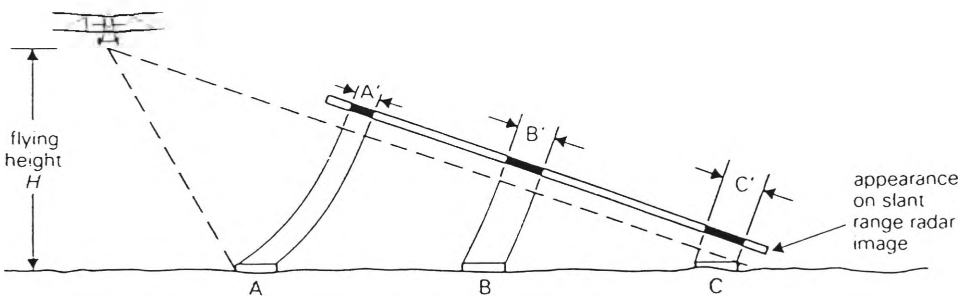


FIGURE 3 Because the whole of its slope which faces the platform is at a steeper angle than a radar wavefront, the top of the mountain is illuminated by the wavefront before its flank and base are. This is translated into slant ranges $-SR_t$, SR_f, SR_b - which produce an image where the top is nearer to the platform than the base or flank is. On the image, the mountain appears to lean towards the platform producing the phenomenon of layover (Drury, 1987).

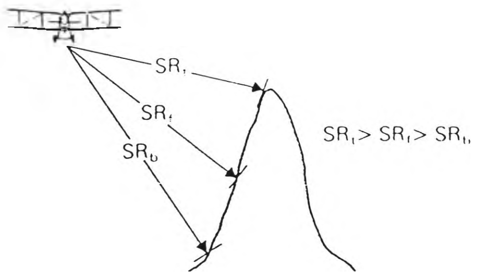


FIGURE 4 Where the surface slope is at a lower angle than radar wavefronts (a) the slant ranges of top, flank and base of a mountain are less than their true ranges on the ground. The result is that the slope facing the platform is compressed or foreshortened. Sometimes the surface has approximately the same angle as a wavefront (b). In this case the slant ranges for all parts of the surface are the same, and the whole slope is compressed to a single line (Drury, 1987).

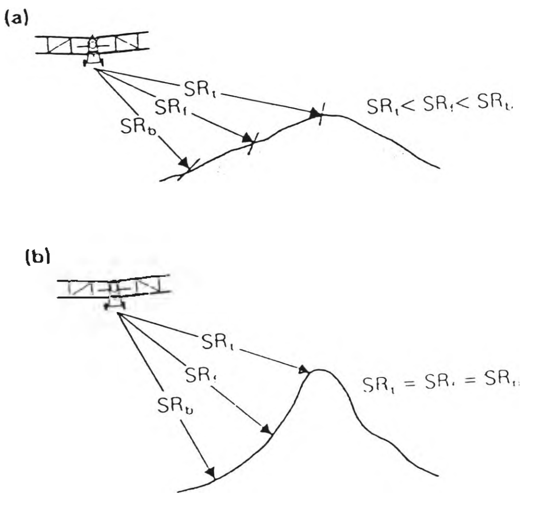
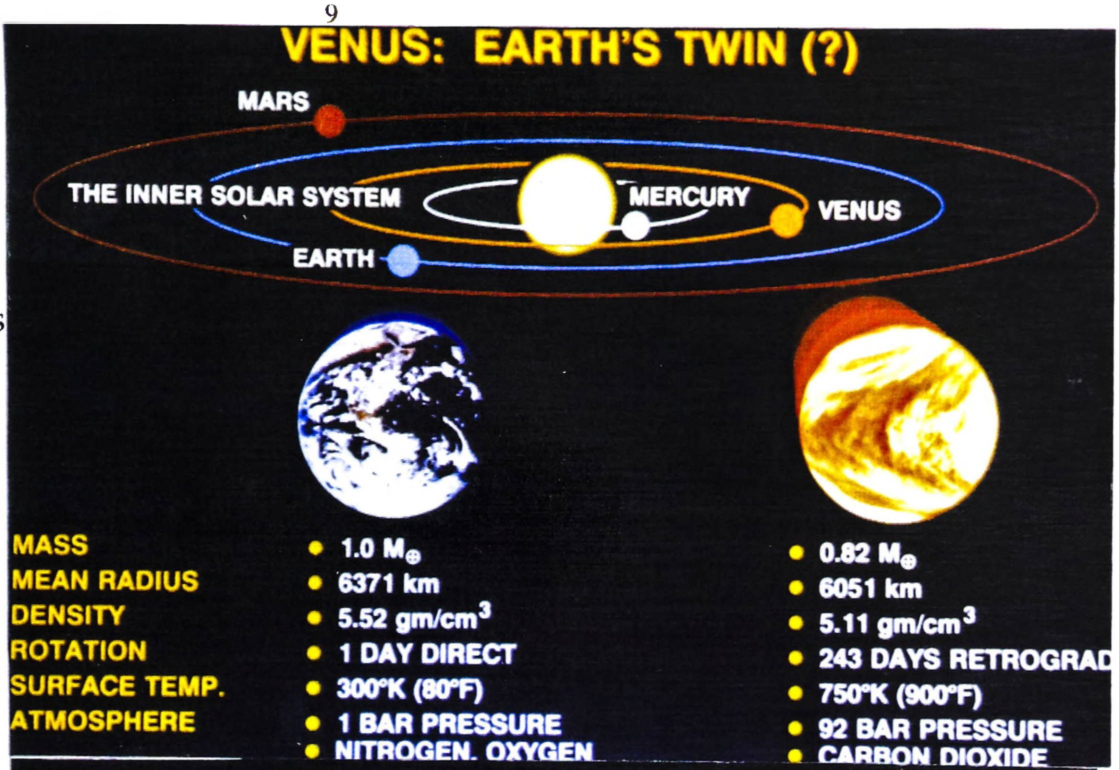
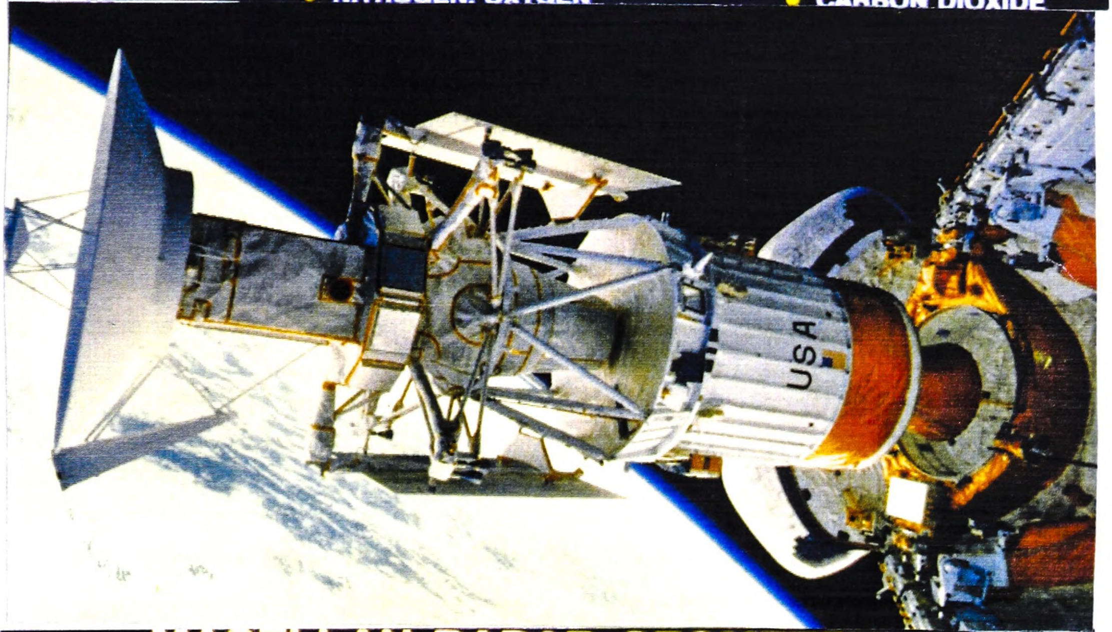


PHOTO 1



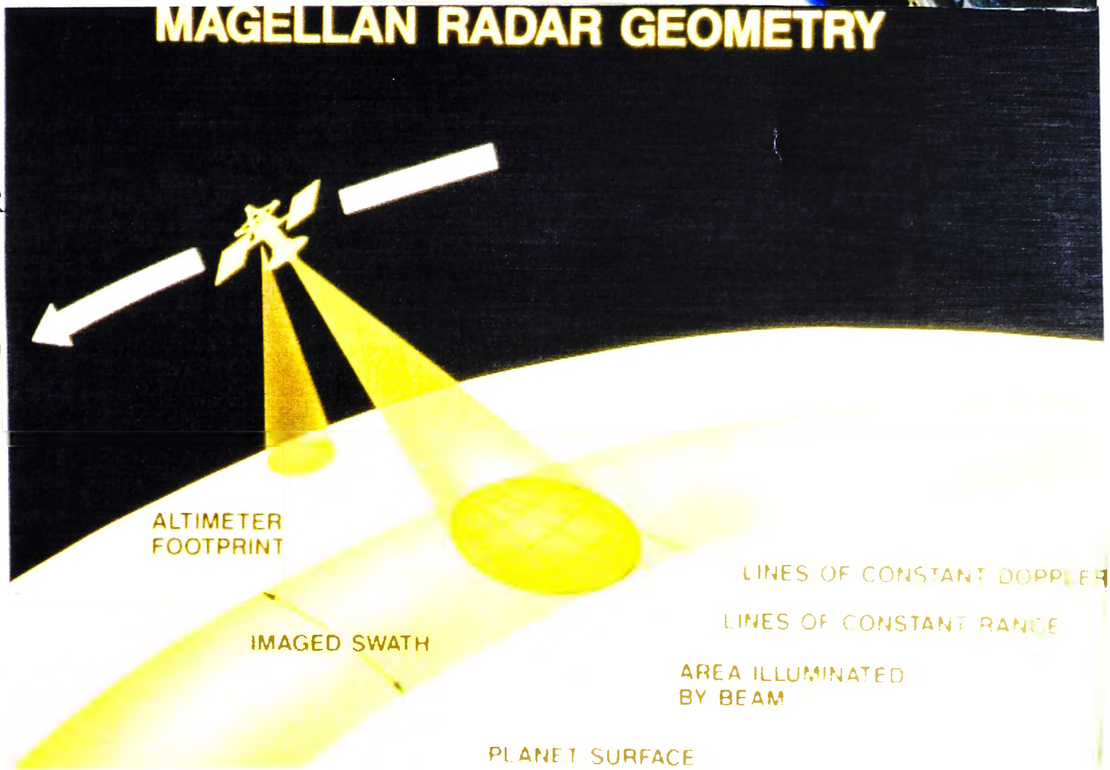
A comparison between the Earth and Venus (Planetary Soc.)

PHOTO 2



The Magellan spacecraft being deployed by the space shuttle. (NASA)

PHOTO 3



Magellans' SAR radar begins imaging Venus. (Planetary Soc.)

1.3.3 MAGELLAN'S MISSION OBJECTIVES

Earth-based and Soviet Venera 15/16 radar images of the Venus surface show widespread evidence for volcanic activity. A major goal of the Magellan mission is to provide a detailed global characterisation of volcanic landforms on Venus and an understanding of the mechanics of volcanism in the Venus context.

Of particular interest is the role of volcanism in transforming heat through the lithosphere. SAR and altimetry data may shed light on magma dynamics, physical properties of lava as well as revealing any evidence for pyroclastic deposits. By characterising tectonic features an appreciation of the tectonic evolution of the planet can be done. Other items to be looked at include processes such as uplift, orogeny, gravity sliding, flexure, compression or extension of the lithosphere.

Impact craters will be scrutinised and both old and young craters located and documented together with their ejecta deposits, in each size range, as well as to distinguish impact craters from those of volcanic origin.

Erosional, depositional and chemical processes on Venus, which are poorly understood, will also be studied by Magellan. This is primarily because certain features on landforms occur at a scale too small to have been resolved by previous radar studies (NASA mission data, 1991).

Thus in summary the mission's scientific objectives were:

(1) to provide a global characterisation of landforms and tectonic features;

(2) to distinguish and understand impact processes;

(3) to define and explain erosion, deposition, and chemical processes; and

(4) to model the interior density distribution.

CHAPTER 2 TERRESTRIAL LAVA TUBES AND CHANNELS

2.1 *How Lava Tubes are formed*

In order to make a comprehensive study of lava flows on Venus we first need to consider those on the Earth, especially those aspects which may be pertinent to conditions on Venus.

When a volcano erupts, lava pouring from its side will follow a path mainly dictated by the surrounding terrain. It may spread evenly, resulting in a lava plain, possibly overlying a previous one. However, if the landform allows, the lava may well be channelled into a valley which means the lava will follow the course of the channel. If the lava remains channelled, the main factors influencing its propagation being, the amount of lava expelled (volume), the eruption time, and the lava viscosity.

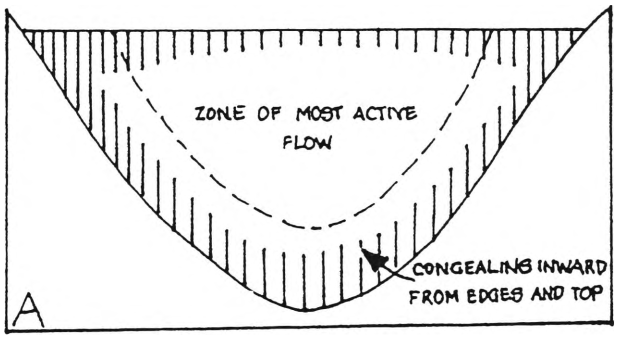
The larger the total output of lava and the lower its viscosity the further the flow will extend along the valley, which may be tens of km on the Earth. As the lava moves along the channel the top and sides of the flow will cool forming insulated conduits for the still molten interiors. When the eruption ceases most of the lava will drain out leaving behind hollow tubes, called lava tubes (Allaby, 1991), see Figures 5 and 6.

Once a lava flow becomes roofed over, it will lose very little heat and may remain molten for some time. One pool of pahoehoe lava 100 m thick formed in Kilauea Iki Crater in Hawaii in Dec.,1959, and on drilling 7 months later, liquid lava was found at a depth of only 6 m and 5 years later was at a depth of 30 m (MacDonald, 1972).

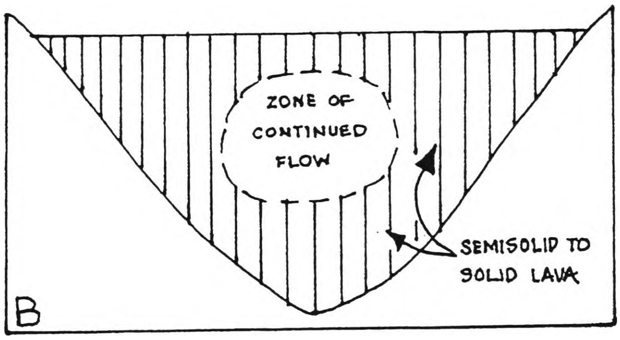
FIGURE 5 - FORMATION OF A LAVA TUBE

Stages observed in the development of the lava tubes in Hawaii (Macdonald and Abbott, 1972). Undara lava tubes also appear to have been formed in this way.

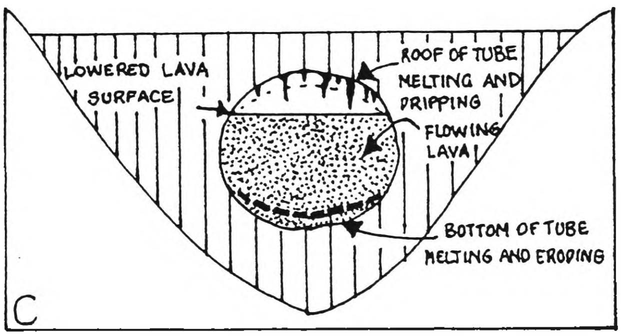
A The lava flow, confined in a valley, develops a thin crust, by one or more processes and starts to solidify inwards from the edges, the centre continuing to flow.



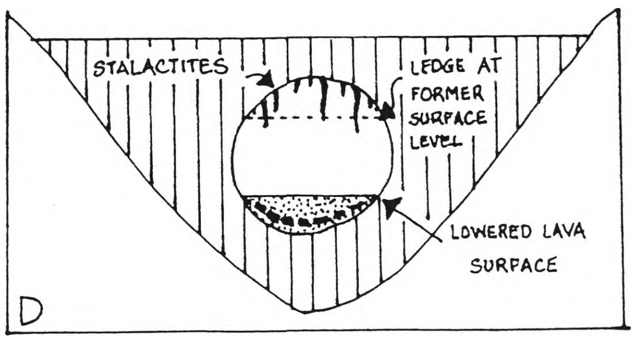
B The active movement of liquid becomes restricted to a more or less cylindrical, pipelike zone near the axis.



C The supply of lava diminishes and the liquid no longer fills the pipe, burning gases above the liquid heat the roof of the pipe and cause it to melt and drip.



D Further diminution of supply lowers the level of the surface of the liquid which finally congeals to form the floor of the tube.



2.2 *How a Flow Propagates*

After a crust forms on the lava the liquid interior still remains mobile for long periods of time, and as long as new liquid is added from the vent it continues to flow. In areas where you have very thick flows, such as the Columbia River region and elsewhere, or flows that are advancing over rather flat and featureless terrain, the spreading of the liquid may be essentially uniform in all its parts. However, in thinner flows such as those of Hawaii, the liquid movement is nonuniform.

Because of irregularies in the underlying surface, the localised nature of the feeding of liquid into the mass, and other irregularies that develop within the flow itself, the movement of the liquid is faster along certain paths within the flow. The loss of heat results in freezing of the less active parts of the flow, and it is only along the paths of most rapid movement, where new heat is constantly being bought in that the interior of the flow remains fully mobile. Thus, there develop pipe-like zones of liquid movement within the much less mobile body of the flow, and it is through these roofed-over pipes that most of the movement of liquid lava to feed the advancing flow margin takes place.

When the supply of magma from the vent is cut off at the end of the eruption or by some blocking of the pipe itself, the liquid remaining in the downslope portion of the pipe may drain away leaving a partly or wholly open tube where it has been.

2.3 *Characteristics of Lava Tubes*

Lava tubes are quite common on the Earth, and as will be argued later, are at least as common on Venus but probably on a much larger scale. Hawaii's Kilauea volcano has a good supply of lava tubes, the full extent of which were unknown until recently (MacDonald, 1972). They are also found in various locations in Australia, with the Undara system in Queensland being considered the best example, which will be looked at in some detail shortly.

The size of lava tubes on the Earth varies considerably. The longest systems may be tens of km in length, while the maximum width appears to be about 30 m. Most are much smaller and some only a few cm wide. The best examples, such as at Undara, may be likened to railway subways or even the new Sydney Harbour tunnel and are about the same size.

Virtually all lava tubes collapse periodically along their length over time, due to such things as erosion and ground movement, making deep penetration difficult. The longest single passages are Leviathan Cave, Kenya (11,122 m); Kazumura in the USA (9,994 m) and Man Jang in Korea (8,994 m) (MacDonald, 1972). Many individual caves are clearly linked as remnants of former continuous caves that were broken by subsequent collapse.

Lava tubes generally have arched roofs, but their floors may be quite flat, formed by the surface of the last liquid lava to move through them. Occasionally, the last lava is viscous enough to form **aa** instead of **pahoehoe**, and the floor of the pahoehoe tube is then covered with a layer of clinkery aa.

In many instances the lava does not drain out at the end of the eruption, and the former feeding pipe remains nearly or entirely full. This is particularly common in flows such as those of flood basalts on lava plateaus or plains that advanced over nearly horizontal surfaces.

Gradual consolidation of the flowing lava results in the deposition of successive layers on the walls of the pipe, and when cross sections are later exposed by erosion or highway construction, the former pipes are marked by concentric circular or oval rings of lava differing somewhat in vesicularity, colour, or both.

In three dimensions, these bodies are nearly horizontal solid cylinders. Their size is comparable to the open tubes. Lutton (1969) has described very large cylindrical structures that differ from the surrounding lava principally in being denser, presumably because they remained fluid longer and lost a large proportion of their gas before they solidified. In the vicinity of the consolidated feeding pipe, the lava is a single massive flow unit as much as 60 m thick, whereas the lava at a little distance from the pipe is vesicular and divided into several thinner flow units.

Therefore, to express the matter simply and in summary, lava tubes are formed by the withdrawal of still liquid lava from beneath a solid lava crust. Actually, the mechanism is very much more complicated. There is considerable controversy on the origin of lava tubes, and there have been four international symposia on the topic, so exactly what is involved is far from settled (MacDonald, 1972).

2.4 *The Undara Lava Tube System*

2.4.1 INTRODUCTION

In this section I will examine in some detail a fine example of a lava tube system, namely Undara.

The Undara volcano is situated approximately 200 km south west of Cairns in the centre of the McBride volcanic province, and I was fortunate enough to study this region at first hand with local experts Anne and Vernon Atkinson. This will help me to make a comparison between it and Venusian systems.

2.4.2 THE UNDARA VOLCANO

The Undara volcano erupted about 190,000 years ago and molten rock poured out of the 340 meter-wide crater at up to 1000 cubic meters a second. The total volume of erupted material was about 23 cubic kilometers and consisted of basaltic lava at temperatures ranging from 1170^0C to 1220^0C, and covered an area of 1550 square kilometers (Atkinson, 1990).

With the surrounding terrain being very gently sloping (Photo 4), average gradient 0.3 degrees, the major flow extended itself for more than 160 km following a course between Junction Creek and the Einasleigh River to become the world's longest known lava flow from a single volcano. To reach such a length, Undara's eruption may have continued for several years.

Considerable study (Stephenson et al., 1976) has shown that the large extent of the flows is due mainly to:

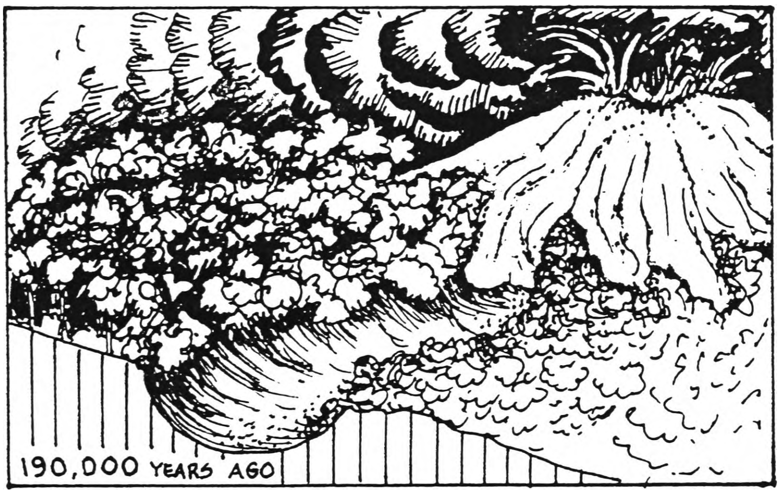
1) **very high effusion rates,**

2) **favourable topography, and**

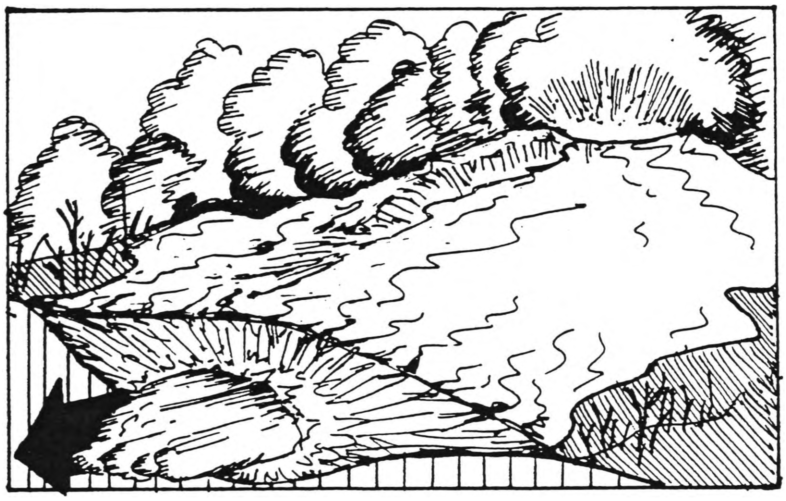
3) **lava tube efficiency.**

FIGURE 6 **HOW THE UNDARA LAVA TUBES FORMED**

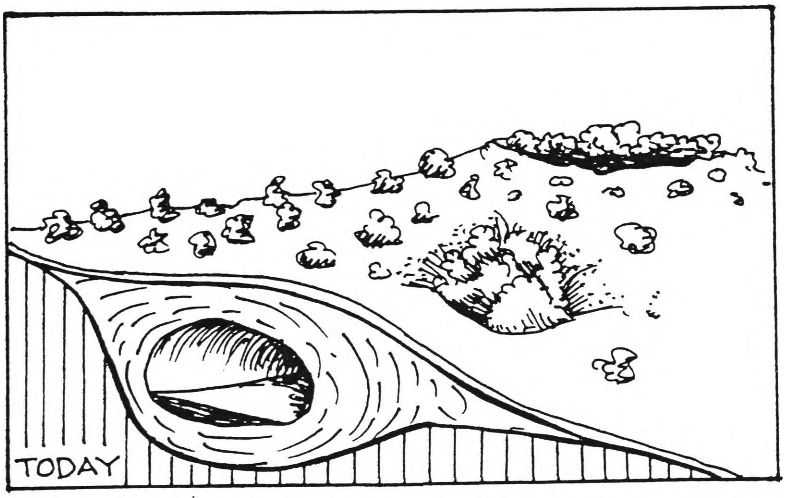
The Undara volcano erupts pouring out lava at up to 1000 cubic metres a second. The surrounding terrain helps channel part of the flow.



The outside section of the lava cools hardening into insulating tunnels around the still-molten interior lava. The molten lava later drains out to leave empty lava tubes.



Time takes its toll on the tubes where weathering causes parts of the tunnel roofs to collapse, forming depressions that harbour vegetation and provide access to the tubes.



NB Photo 5 shows a piece of lava tube.

Another section of the flow followed the Lynd River for about 90 km. Although the lava flowed in all directions, most was to the north and west, channelled in part by dry river beds (Figure 7). The rivers of molten rock upon cooling formed a crust, much like the skin on custard. This skin and the sides of the flow hardened to form insulating tunnels that kept the interior lava molten and flowing down the valleys and across the gently sloping plain. As the volcano reduced its output of lava, the last of the lava drained out of the tunnels to leave behind hollow tubes.

One of these, Bayliss, is about 20 m wide, up to 11.5 m high and is at least 1350 m long, being the longest and largest lava tube in Australia. However, most of the 60 caves and arches that have been discovered so far in the area are less than 200 m long.

The tube roof, being only from 1 to 10 m thick, can become unstable over time due to erosion, Earthquakes and other factors. Despite this, the caves appear generally quite stable, free of debris and remarkable well-preserved. To date more than 6 km of tubes have been surveyed. The lava tube system extends more than 110 km and includes caves, arches, and consists of a low level ridge, which is up to 20 m high, and 35 km long, known locally as "The Wall'. This ridge is considered the best Earth volcanic feature analogous to the smaller basaltic ridges on the moon.

Although, lava tubes may be very complex in plan, interconnecting and multi-level, almost all at Undara are simple in plan and appear to be single-level.

The lava tube system at Undara has been divided into the following 5 sections (Atkinson, 1990) as seen in Figure 7 below:

1) Crater Section- extends 4 km north from the Undara crater with an average slope of 1^0.

2) West Section- extends about 15 km west of the crater with a slope averaging 0.75^0 .

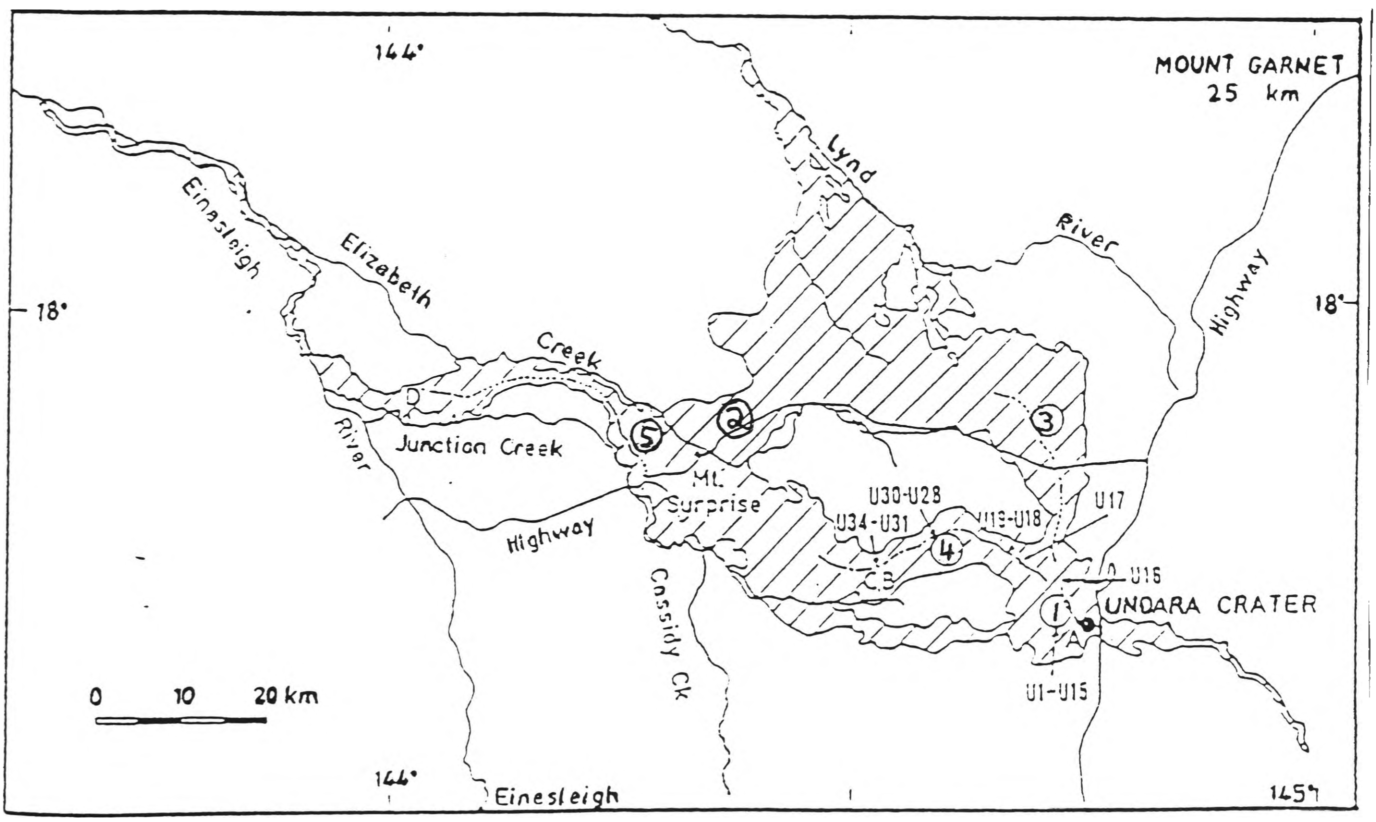
3) North Section- extends north of the crater section for at least 18 km and maybe up to 28 km, the average slope is 0.5^0.

4) Yarramulla Section- extending WNW from the northern end of the Crater Section for over 35 km, average slope 0.7^0.

5) Wall Section- extends approximately 35 km maintaining an almost continuous narrow ridge, known as "THE WALL", average slope 0.09^0.

<u>FIGURE 7</u> THE UNDARA LAVA FIELD

Circled numbers denote sections of the lava tube mentioned above, namely: 1, Crater Section; 2, West Section; 3, North Section; 4, Yaramulla Section; 5, Wall Section. Other numbers are locations of cave entrances. Letters "A" to "D" denote locations of basalt samples (Atkinson, 1990).



The Crater, the West and the Yarramulla Sections contain both caves and arches. A line of collapse depressions indicated the presence of a lava tube in the North Section where none had been previously found and it wasn't until 1989 that a systematic search uncovered 3 caves (Atkinson, 1990). No access to a tube has yet been discovered in the Wall Section. It appears to be either a solid tube or as geologist Anne Atkinson believes a major lava tube with a very thick roof.

Following the caves and arches along a similar line are oval and elongated depressions. These depressions are generally much wider than the caves and arches and seem to have formed at the same time as the tubes by offshoots of lava ponding, than later draining away. Dark green "rainforest" type vegetation gives these wider depressions away especially in aerial photographs (Figures 8, 9 and 10) since they contrast sharply with the eucalypt woodland found in the surrounding plain.

The Undara lava field is mostly of the smooth "pahoehoe" type, a part "aa" basalt being found in a section to the north. Current thinking, based on records and observations, is that lava type, pahoehoe or aa type basalt is determined by volumetric flow rate. Those in Hawaii that formed at the lower flow rate being pahoehoe, which allowed time for de-gassing (Rowland and Walker, 1990). This is important since it is pahoehoe flows that the long terrestial lava tubes have formed from and probably elsewhere, as will be discussed later. The Undara lavas are all Hawaiites and are mostly of uniform composition.

Investigations by Walker (1972) and Stephenson and Griffin (1976) has led to the conclusion that the Undara lavas appear <u>unlikely</u> to have possessed unusual viscosities (10 to 30 Pa s).

PHOTO 4

The Undara crater can be seen in the distance at the centre of the picture. Note as well the surrounding flat terrain.

PHOTO 5

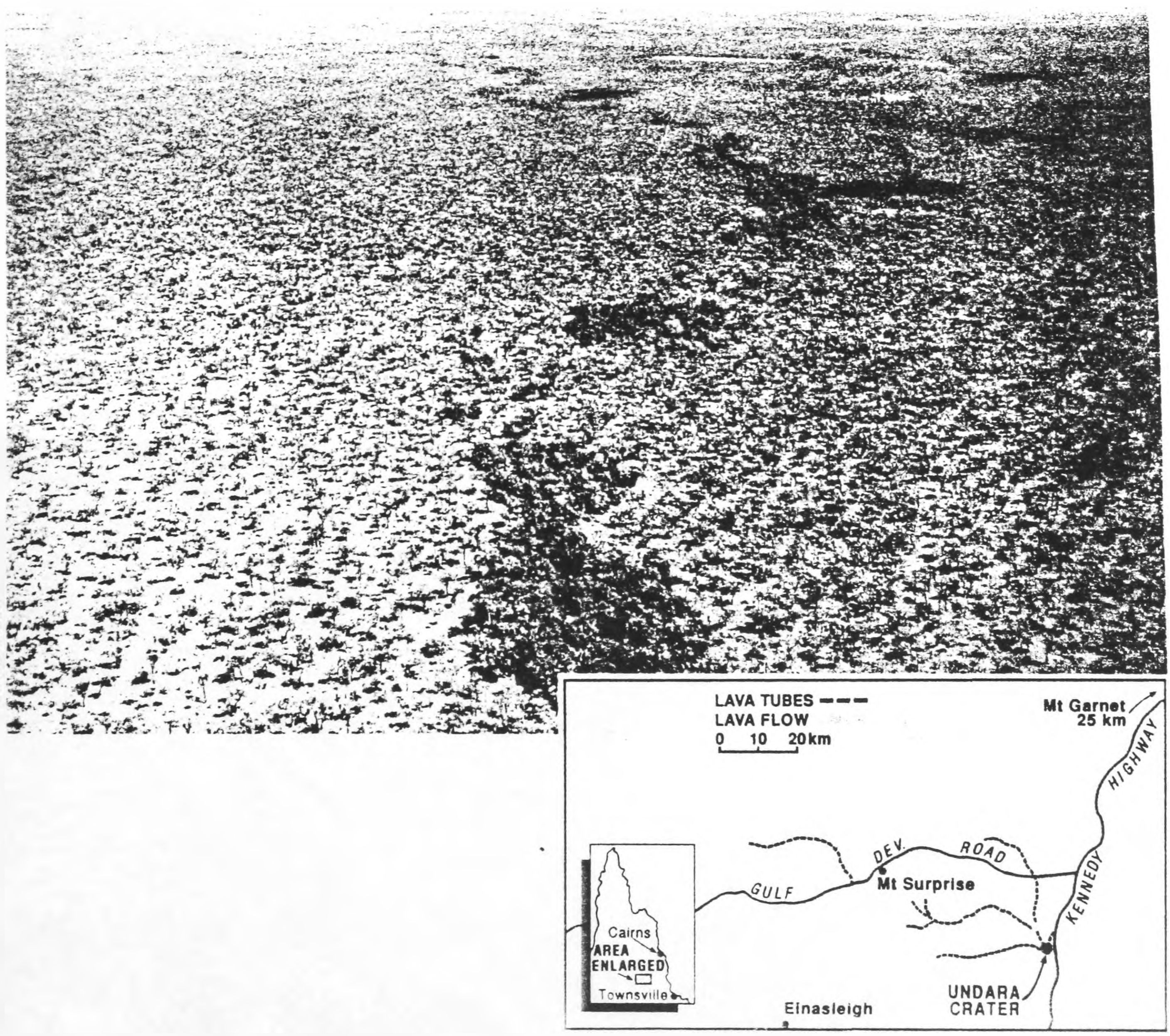
The upper surface of a piece of lava tube. Notice its relative smoothness as well as the flow patterns.

PHOTO 6

Inside the lava tube. This is Barker Cave, 50 meters from its entrance. Note the gutter on the left, the ropy floor and the lava level lines evident almost to the roof on the distant wall. (Photo H.J.Lamond-James Cook Univ.)

FIGURE 8 A LAVA TUBE'S COURSE

A broken line of darker vegetation marks a lava tube snaking it's way across savannah woodland. Vine thickets survive in the depressions where sections of the lava tube roof has collapsed. They both identify and conceal entrances to some 60 tube sections formed when Undara erupted 190,000 years. The lava covered 1550 sq. km and flowed for 160 km to become the world's longest flow from a single volcano.



<u>FIGURE 9</u> THE UNDARA CRATER SHOWING A MAJOR TUBE

A lava tube (dark section) leading away from the central crater is revealed by contrasting vegetation that inhabits the collapsed sections. (Photo-Dept. of National Mapping).

<u>FIGURE 10</u> UNDARA'S CURVING LAVA TUBES

The weaving path of one of Undara's major tube sections making its way from the once active volcano, follows the route of least resistance.
(Photo-Dept. of National Mapping).

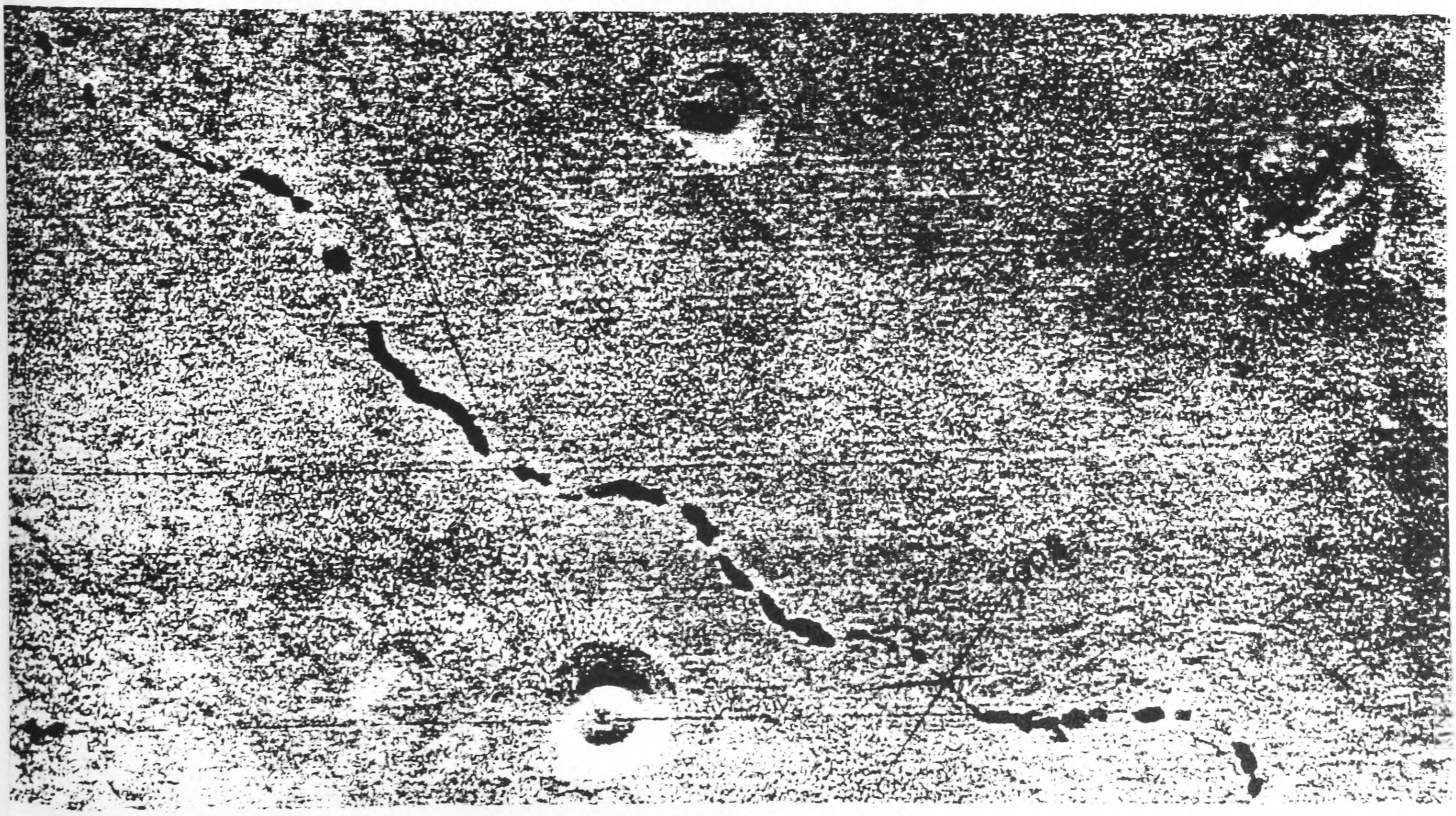
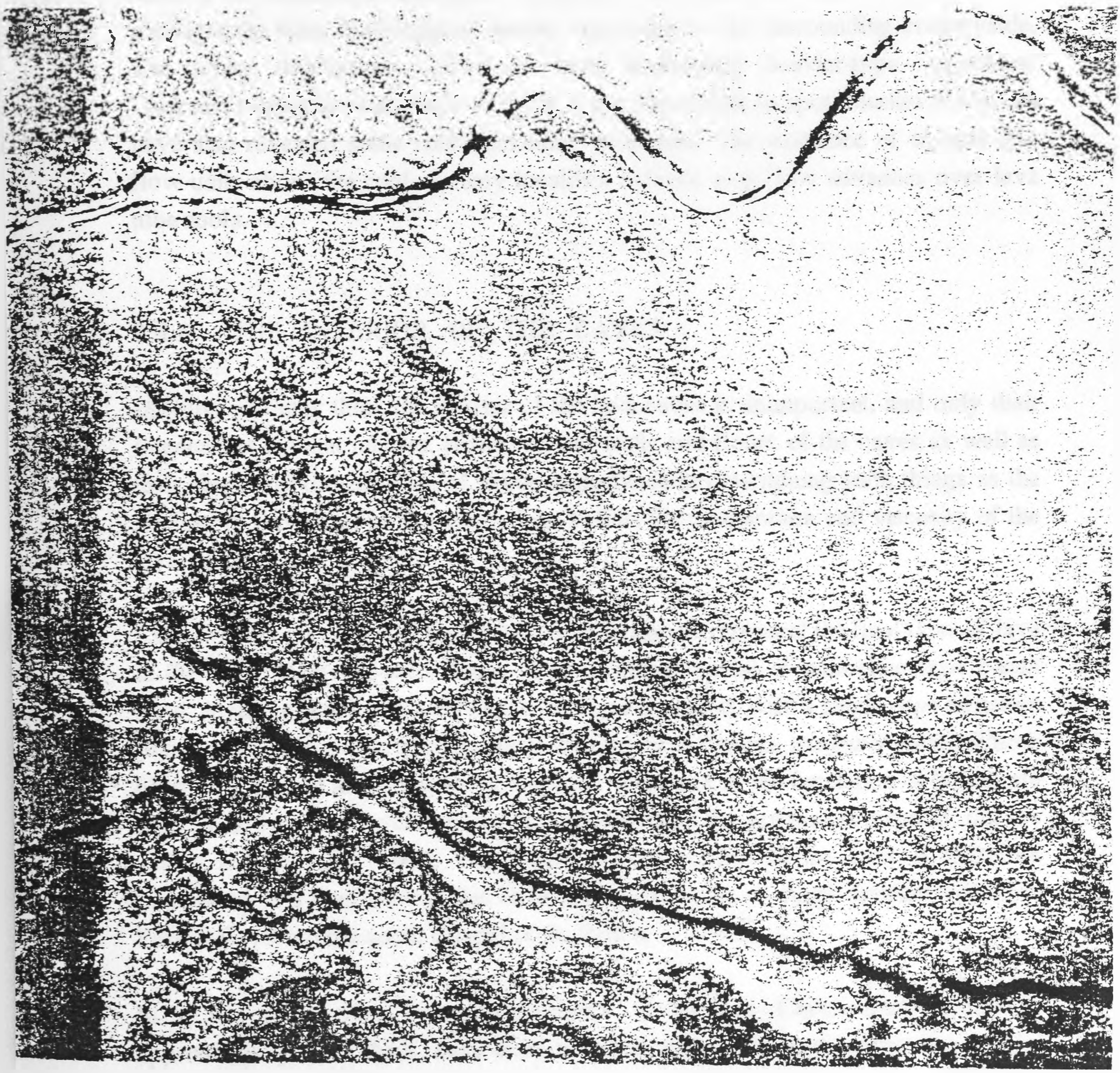


FIGURE 11 "THE WALL"

This is a *raised* lava tube (bottom) or basalt ridge. It is considered the best known example of such a feature and is analogous to some of the basaltic ridges on the moon. This feature is 35 km long and the section on the left in the picture has overflowed and spilled into the surrounding countryside. The top white snake-like feature is a creek bed. (Photo-Dept. of National Mapping).



2.4.3 THE LOCATION OF THE CAVES

The location of the drained lava tubes could only be positively identified by the tunnel-like caves or their collapsed extensions. Access to the caves is gained where debris from roof collapses has not completely blocked the underlying tube, or through 'skylights' (Photo 7) which developed while the tube was still active (Peterson and Swanson, 1974).

Most of the depressions that give way to cave entrances are difficult to spot on air photographs since they support similar vegetation to the surrounding countryside. The wider depressions, however, have contrasting heavier-type vegetation. Undrained tubes are extremely difficult, if not impossible to spot. Studies at Undara have also revealed some roof thickening processes. The existence of several thin flow units above the roof at many localities indicate new flow advances over lava tube roofs.

2.4.4 THE INTERIOR OF THE CAVES

Initially, one may think the interior of the lava caves is unimportant, and only their dimensions is what matters. However, the walls and floors of the caves as well as their slope and direction are of prime importance in determining such things as the number of flows that have occurred as well as the temperature and viscosity of the lava, among other things.

Cave floors when not covered by water or sediment, represent the final flow of lava in the tube. Most exposed floors show features typical of pahoehoe type basalt flow. At the entrance to Barkers cave the floor is arched, with a single rope structure running down-flow. As one proceeds into the cave distinct *marginal gutters* (Photo 6) up to 1 m deep are found along the floor. Evidence of the formation of levees are seen as the fine lava level lines on the outer walls of the gutters correspond, but are absent on the inner walls. The raised central portion of the cave is therefore interpreted as a final flow in this cave. Good examples of *ropy lava* are visible in Pinwill Cave and the south Chapel of St. Paul's.

In a central position near the entrance to Barkers Cave, crust fragments, approximately 8 cm thick, have been rafted at varying oblique angles in a similar way to ice slabs on a frozen river.

In Peterson Cave, there is a small floor surface where lava drops from roof re-melt appear to have pitted the floor, much like raindrops would pit a muddy surface. Prolonged flow at a constant level is evidenced by the "*pavements*" in Taylor Cave (Figure 12). Where the rate of flow is less against a convex bank, lava consolidates in a manner similar to the deposition of alluvium on convex banks of rivers.

Most of the caves have a lava lining on the walls and roof. Typically the lining is a single layer up to 20 cm, but may approach 1 m in thickness in some places. At various locations the tube lining has fallen off the wall exposing the host lava behind it. The lining is sometimes multi-layered (Photo 8), the best example is in Pinwill Cave where 15 layers, 2-4 cm thick are revealed at one location.

There are some areas of very low vesicularity on most cave walls and roofs and show drip and dribble structures resembling cake icing. These surfaces are seen as having being remelted, due to the ignition of volatile tunnel gases, and because of their lustre are appropriately termed "*glaze*", but the Undara tubes exhibit only a dull lustre due to weathering.

In some places there are *lavicicles (lava stalactites)*, commonly 2-3 cm and occassionally up to 8 cm long, suspended from places such as roofs, inclined walls and wall cavities. Lava stalagmites are rare, as are lava columns. No "straw" stalagtites have been found - no doubt because of their extreme fragility.

FIGURE 12 TAYLOR CAVE

The prominent "pavements" (1 and 2) are evidence of an extended period of constant rate of flow. Solidification has been greatest at the apex of convexity, as in a fluvial river. There is a cylindrical opening (3) in the roof, its location suggests that some lava which ponded close by, may have drained back into the tube through this conduit (Atkinson, 1990).

2.4.5 TERMINATION OF THE LAVA TUBES

The caves generally terminate down-flow with collapses, or with a gentle downward curve of the ceiling to a silt floor. Barkers Cave ends in a lake, the ceiling steadily declining to water level. Several caves have down flow entrances and have little or no silt on their floors. Pinwill Cave, The Opera House, Picnic and Wishing Well Caves terminate with walls.

2.4.6 DEPRESSIONS

A study of lava tubes would be incomplete without a reference to the collapse depressions. As will be discussed later, these depressions are analogous with some indentations found on Venus.

These depressions are divided into two types:

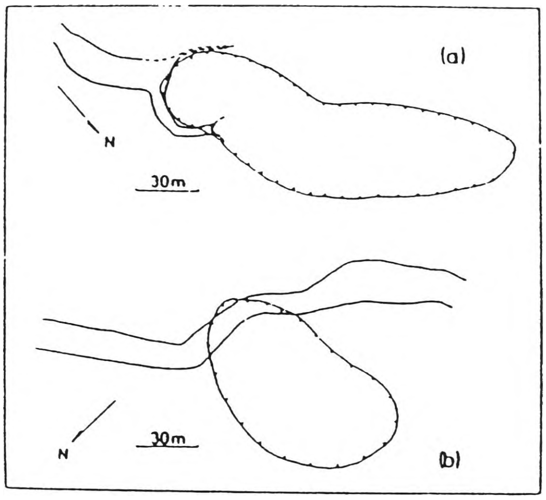
1) **Narrow Depressions**- these are 30-50 m wide and commonly give entry to the lava tube caves suggesting that they were formed by the collapse of segments of the tube. Vegetation within these depressions, as previously mentioned, differs little from that of the surrounding countryside making them difficult to spot.

2) **Wide Depressions**- these are 50-100 m wide and form a strong linear pattern. They seldom give access to caves and have distinguishing features from the narrow depressions. They are usually oval or circular in shape, and tend to become elongated in the direction of the lava flow. Most wide depressions have elevated rims, suggesting that they represent former lava ponds like some of those seen in Hawaii which form where the slope is small.

Once formed, the ponds tend to perpetuate themselves during the life of the flow, even when the flow front has advanced further (Figure 9). These ponds crust over and remain interconnected with the lava tubes that have progressed ahead. The crusted surfaces of these ponds have been observed to subside as the flow dwindles and the ponded lava drains back into the tube. Sometimes the collapsing pond may interfere with the still functioning tube, as is believed to be the case with Taylor Cave.

FIGURE 13 LAVA PONDING AND CAVES

This diagram shows the relationship between surface depressions and caves:
a) Taylor Cave b) Barker Cave (after Atkinson, 1990).



2.4.7 THE "WALL"

The Wall (Figure 11 and Photo 9) consists of a very long narrow ridge that rises up to 20 m above the general level of the flow and can be traced for 35 km. The top of the ridge is quite flat and may be from 70 to 300 m wide. Its down-flow slope averages only 1.72 m per km with occasional undulations. The side slopes of the ridge are up to 29^0 and there are several depressions within 2 km of the wall's termination. One of these depressions may represent a collapsed lava pond which drained to the tube below.

The tongue of lava surmounted by the Wall flowed down a precursor of Junction and Elizabeth Creeks. Functional water bores in the vicinity of the Wall confirm that the narrow ridge is localised above a former stream bed.

PHOTO 7

A 'sky-light' entrance to one of the lava tubes. Collapsed roof, in the form of rubble, usually surround these entrances.

PHOTO 8

Multi-layered lava lining on one of the cave walls. These indicate different levels of lava flowed through the cave. A torch gives an indication of scale.

PHOTO 9

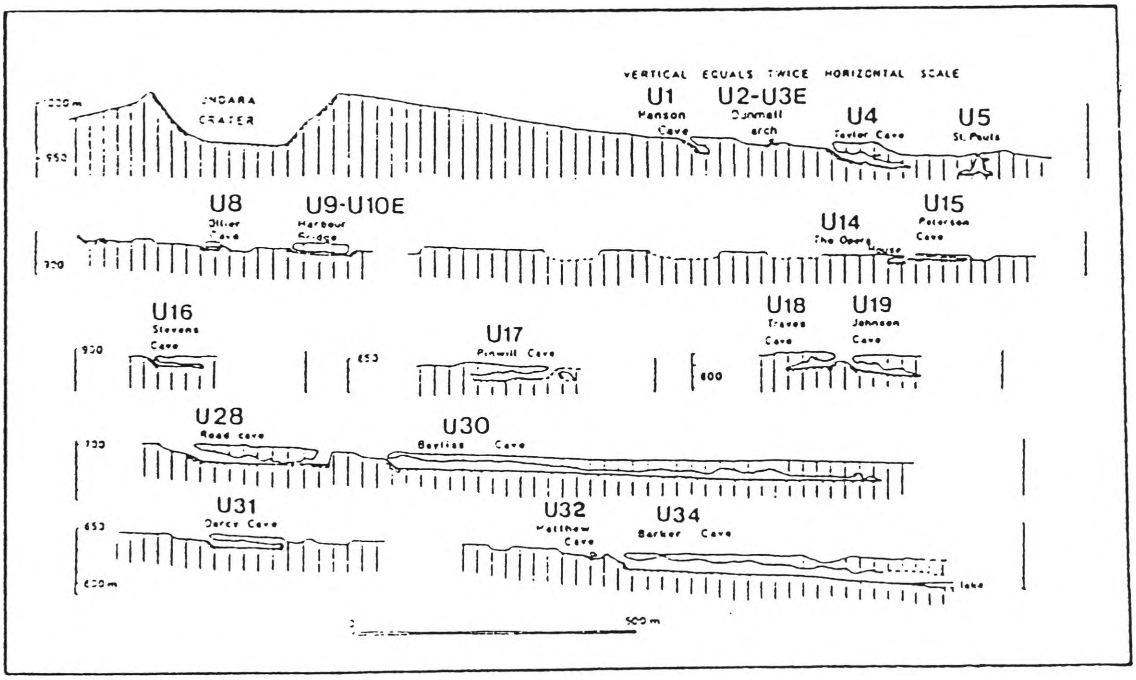
A section of "The Wall" partially cut by a roadway is seen here.

FIGURE 14 DIMENSIONS OF SOME OF THE CAVES (Atkinson)

CAVE	LENGTH	MAX. HEIGHT	MAX. WIDTH	AVERAGE SLOPE
Taylor	108 meters	10.8 meters	16.3 meters	2 55 (Deg/Min)
Ollier	49.4	3.2	10.4	0
Greeley	103	3.8	12.4	1 45
Peterson	102	3.7	17.1	0 40
Stevens	70.4	3.0	8.8	1 20
Pinwill	150	8.8	21.0	0 50
Road	220	9.4	21.2	0 50
Bayliss	901	11.5	18.9	1 10
Darcy	99	6.3	16.3	0
Barker	561	13.5	19.8	2 10

FIGURE 15 CAVE PROFILES

Longitudinal profiles of various caves down flow from the Undara Crater. Floor symbols: Sediment (.....), Ropy Lava (/////) (Atkinson et al.,1975).



2.4.8 SUMMARY AND CONCLUSIONS

1) The Undara volcano erupted 190,000 years, sending forth about 32 km^3 of lava, covering 1550 km^2.

2) A major lava tube system lies well preserved and extends over 110 km. Lava tube collapses have led to narrow depressions publicising cave entrances, where caves may be up to 1 km long and 20 m wide.

3) The lava tubes probably developed by the roofing over of lava channels.

4) Within the caves and arches, protection from weathering has allowed the preservation of many features similar to those in active and recent lava flows indicating that they formed from eruptions of pahoehoe lava.

5) Wide depressions probably represent collapsed lava ponds.

6) A narrow ridge, 35 km long is believed to have contained a lava tube.

7) The Undara lavas are all Hawaiites of nearly uniform composition. They do not possess any unusual properties and are thought to have had normal viscosities.

8) The unusual length, 160 km, of the Undara flow developed on very gradients (average 0.3^0). It resulted from a very high rate of lava effusion coupled with favourable topographic channelling and an efficient lava tubes system.

CHAPTER 3 VENUSIAN LAVA TUBES AND CHANNELS

3.1 *Introduction*

Venusian images[2] are available at 4 different resolutions.

F-Mosaics - these are the highest resolution images, with their 75 m pixel widths.

C1-Mosaics - have a pixel width of 225 m.

C2-Mosaics - have a pixel width of 675 m.

C3-Mosaics - are the lowest resolution images, with a pixel width of 2.025 km.

Since many aspects of lava structures occur on small scales it was decided to make use of the best resolution images available. This entailed studying F1-Mosaics (616 x 539 km), with each Mosaic consisting of 56 smaller images. These FF sub-images are 77 x 77 km. in size, and have a range resolution of 80 m, and an azimuth resolution of 120 m. This means the smallest objects that can just be resolved is about 120 m (NASA mission data, 1991). This high resolution is very important as will be seen shortly.

The 28 F1-Mosaics were chosen so that a wide, roughly evenly distributed sampling of the planet was obtained. This amounted to more than a 20% coverage (Figure 17) of the planet at high resolution. An altimetry map of Venus with a similar scale for comparison is provided in Figure 16.

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[2] These images are supplied by NASA on CDs to research groups.

FIGURE 16 **ALTIMETRY OF VENUS**

This altimetry map of Venus showing in colour the heights of different areas is a convenient aid in developing a more complete 'picture' of the research area when a comparison with Figure 17 is made (Planetary Soc.).

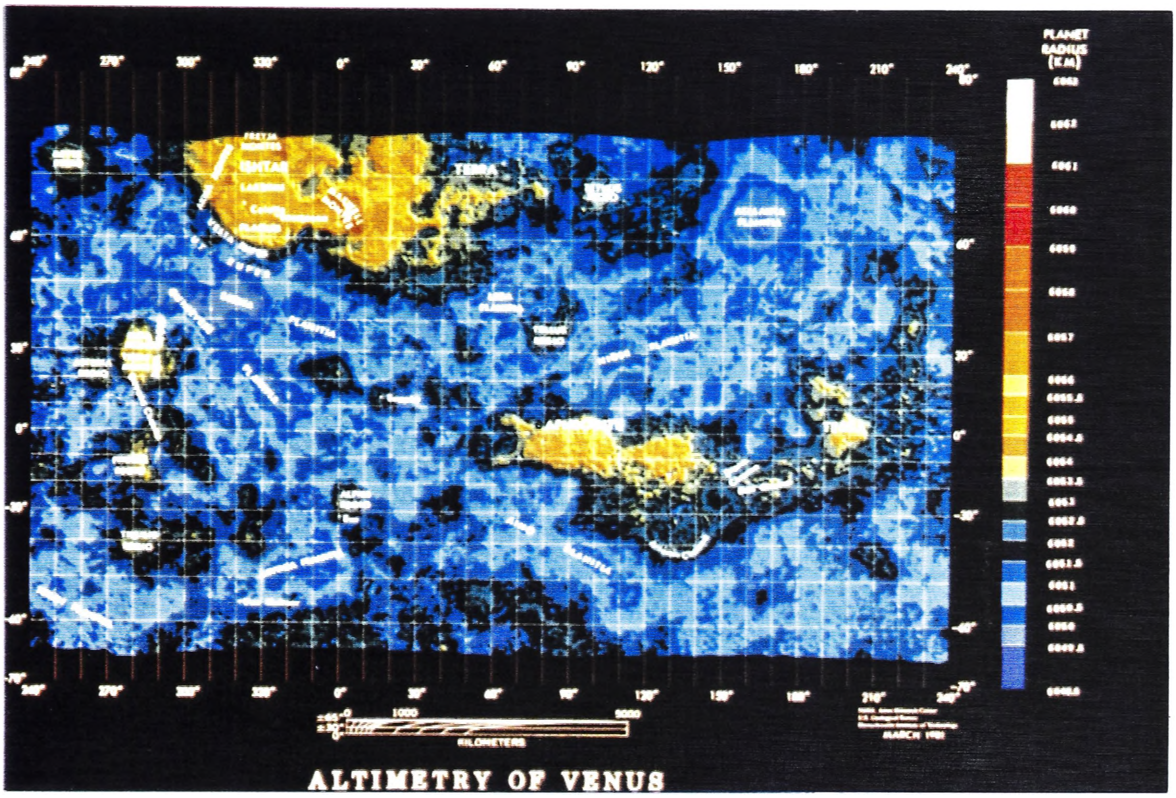
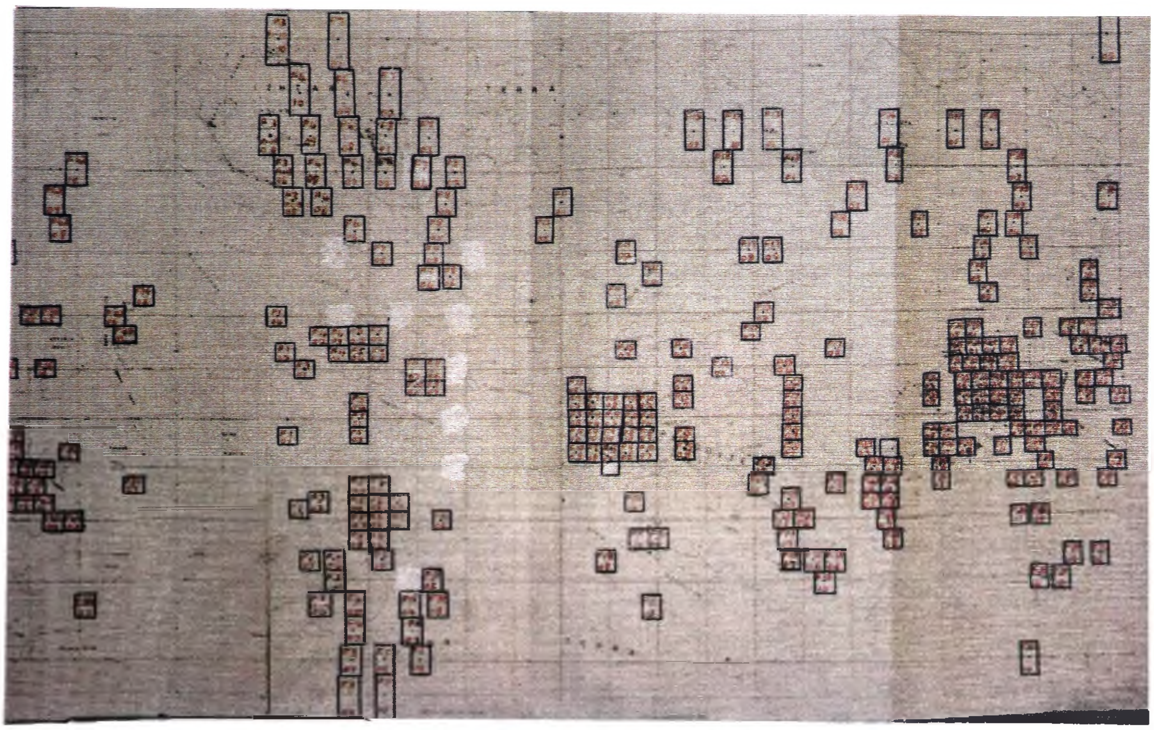


FIGURE 17 **VENUS SURVEY**

The regions of Venus surveyed in this research are shown below. Each box-like, F-Mosaics, region represents an area **616 x 539 kms** and are of equal areas. Their total area represents a coverage of more than **20%** of the Venusian surface.



3.2 *Venusian Lava Tubes and Channels*

There appear to be three types of structures associated with the transfer of lava :

TYPE A - **Surface Lava Rivers**- these are similar in appearance to terrestial watercourses. They may also be divided into 2 catagories. Those that have somehow become drained, and those which are relatively unemptied.

TYPE B - **Crater Chains**- these consist of individual craters varying from 120 m (the limit of resolution) to over a km in diameter. The length of these chains are on average 25 km, but range anything from a few km to over 100 km in length.

TYPE C - **Indentations**- These usually appear as long furrows which are normally closed at both ends. Although most are long and narrow, shorter oval ones are not uncommon.

These will now be looked at more closely.

<u>NOTE</u> IN REGARD TO VENUSIAN PICTURES THE FOLLOWING SHOULD BE NOTED:

1. pictures are <u>radar</u> images and have been illuminated from the <u>left</u>. north is upwards.

2. <u>rough</u> areas appear bright whereas <u>smooth</u> areas appear dark.

3. THE Magellan radar operates at <u>12.6 cm</u> so smooth and roughness is <u>relative</u> to this scale.

* 4. <u>the unavailability of altimetry data</u> at the time of analysis makes the direction of lava flows and possible <u>slope directions</u> very difficult to interpret.

3.2.1 TYPE A - LAVA RIVERS

These, as mentioned, are similar in appearance to terrestial rivers and are analogous with Earth lava streams (Photo 10). Although, these Venusian lava rivers are relatively common and have connections with crater chains and indentations they are not the main area of study for this thesis and will not be looked at in any great detail. However, because of their connection with lava tubes, that is, lava rivers may roof over forming lava tubes, various aspects regarding the flow of lava needs to be addressed.

If a sizeable amount of mobile lava becomes available at a point source such as a vent in a volcano, some type of lava river will form. This lava will follow a path dictated by the local topography with the extent of this river being governed by both the viscosity of the lava and the total volume of lava expelled. The lower the viscosity, the greater the volume and the more favourable the terrain, the further the lava river will extend.

Venusian lava rivers, like their terrestial counterparts, are often **sinuous** in appearance (Photo 11), but some show mature **meanders** (Photos 12 and 13), unlike those on the Earth (Photo 14). This indicates that some Venusian lava rivers have flowed over a longer period of time or at least have been reworked over time. This means the continuously flowing lava behaves much like eroding watercourses on the Earth, resulting in escavation of the channel (Carr, 1974) as seen in Photo 10.

Many Venusian lava rivers seem to be far bigger (especially in width) than any on the Earth, some being as much as 400 km long and 3 or more km wide. Typical Earth lava rivers are only tens of meters wide and rarely more than 20 or 30 km long, the maximum being around 100 km in length (Saunders, 1993).

The question which comes to mind is 'if the lava rivers are longer on Venus than the Earth, does this mean, on Venus lava is more plentiful, the topography is more suitable to long flows, or the lava is behaving differently for some reason?'. Baker et al., 1992, classified the lava channels into 4 major classes based on morphology.

They are :

1) Simple -have a long, single main channel eg. photo 10 & 11

2) Complex -have branching or braided patterns e.g. photo 13 (bottom section).

3) Compound -have simple and complex segments

4) Integrated -have a series of crisscrossing networks.

Note The longest Venusian channel, discovered to date, originates at 44.5^{0}N, 185^{0}E and terminates 11.5^{0}N, 167^{0}E in a radar dark deposit and is called Hildr Fossa. It is about 6800 km long. This channel is developed mostly on lava plains units, north of Rusalka Planitia. Despite disruption by cratering and volcanism, it appears to be a single channel (Saunders, 1993).

The Availability of Lava on Venus

On the Earth basaltic magma is believed to come from the outer part of the mantle. This rises through channels and accumulates a few km below the surface in magma reservoirs which may later be used in eruptions.

Little is known for sure, either about the availability, or origin of Venusian magma but it appears reasonable to assume at this stage that it does not differ considerably from the Earth in this regard. However, at Undara, the large extent of the lava flow was chiefly due to the very high effusion rate.

PHOTO 10 - F55S355(FF15) on the next page shows a branching Venusian lava channel.
It is located southeast of Lavina Planitia near 55 degrees south latitude and 355 degrees east longitude (longitude on Venus is measured from 0 degrees to 360 degrees east). The channel itself extends beyond the picture being over 100 km long and 1.5 km wide.

The channel is clearly excavated and appears to be clear except, for possibly, the far left section where a small amount of smooth lava appears to have remained in the channel. Lava direction is uncertain, though, the sharp point where the two branches meet hints that the lava may have flowed to the left since a flow in the other direction would probably give a more rounded appearance to this section.

The flow which formed this channel appears to have come from relatively fluid lava and was well-confined to the channel with no obvious overflows visible. North is at the top of the image.

PHOTO 11 - C1-00N335(C1F21) also on the next page, shows a sinuous smooth (dark) lava flow, located on the equator northeast of Navka Planitia at 0 degrees latitude and 335 degrees longitude. The flow, over 300 km long, also appears to have formed from relatively fluid lava. No spills are evident and the smooth surface within the channel probably indicates some lava remained in the channel.
Note the lava river is superimposed on top of the cracks/wrinkles which indicates the channel is younger than the surrounding area. Also it has probably cut down into the terrain since the flow has not spilt into these cracks.

PHOTO 10
A branching
escavated
lava channel.
(F55S355-FF15)

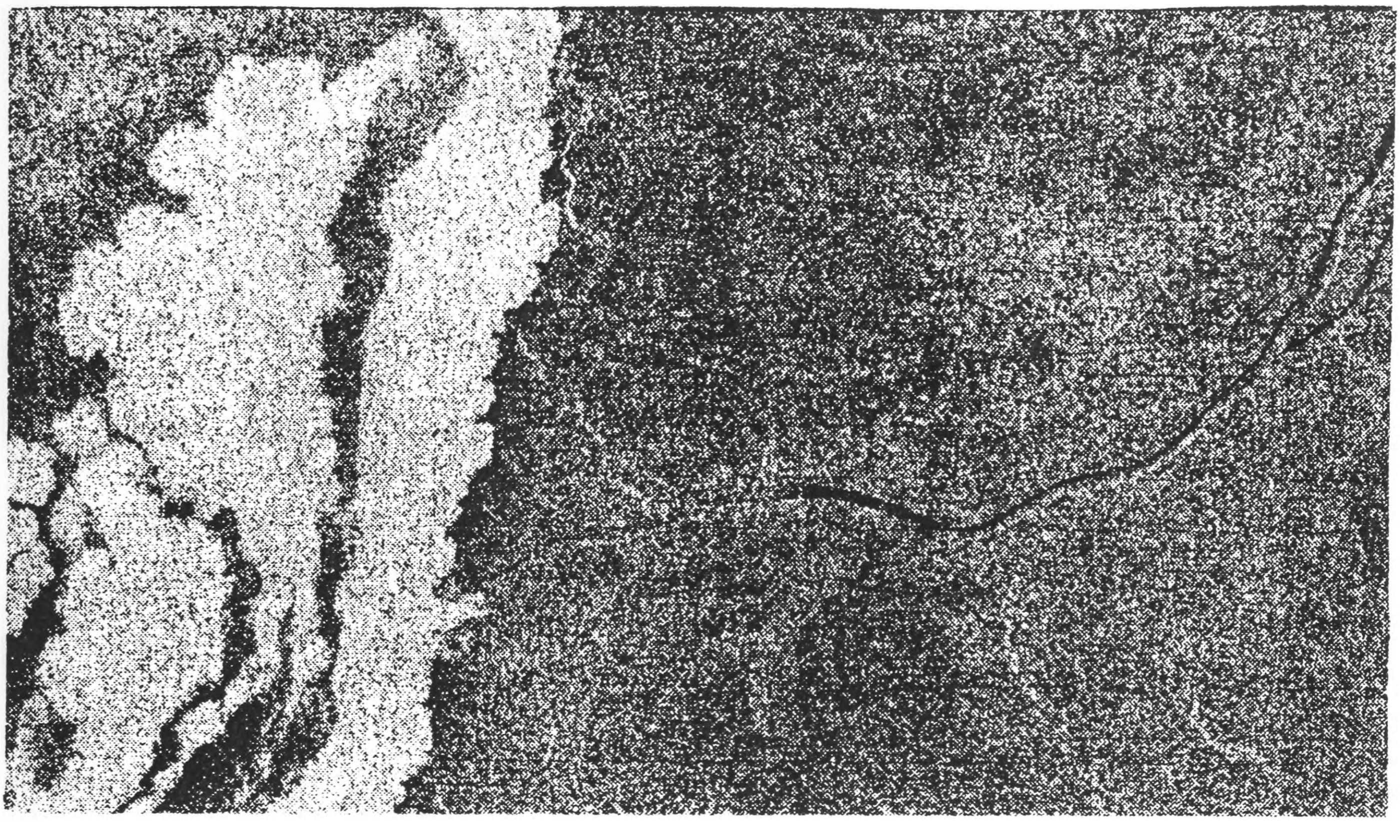


PHOTO 11
A sinuous
lava channel.
(C1-00N355)-C1F21

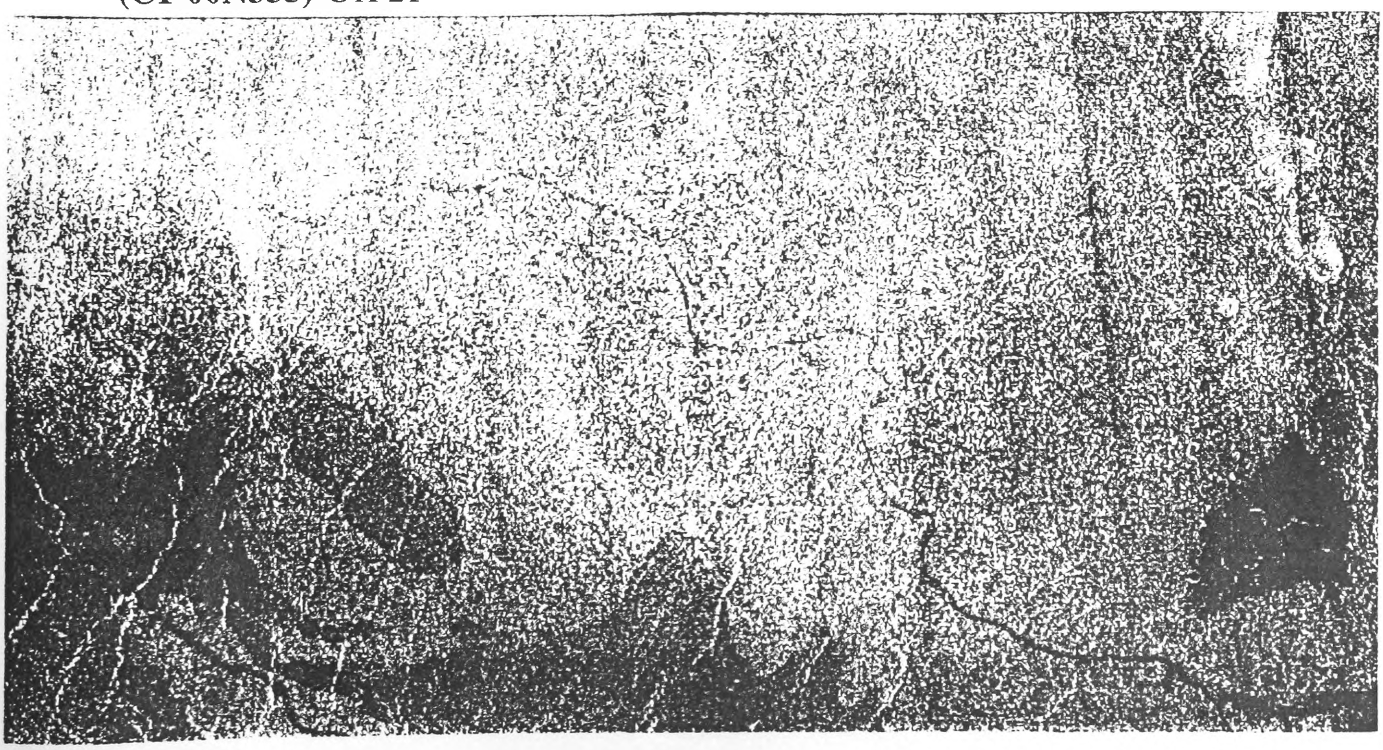


PHOTO 12 - F45N019 on the next page shows a mature meandering lava channel. It is located near 45 degrees north latitude and 019 degrees east longitude. This channel is over 400 km long and about 2 km wide, the full extent of which can be more easily seen in Photo 13. Distinct cutoff channels and local branching patterns are also evident and the white snowy section along most of its length indicates a levee bank may have been formed. The eastern-most section is not as defined but the channel path is still visible. A few cinder cones can also be seen.

PHOTO 13 is a larger scaled view of Photo 12 with the lava channel visible towards the left of center. The direction of flow is from top to bottom, down a regional gradient sloping from Fortuna Tessera south into the ridged plains of eastern Sedna Planitia. Lava channels of these type are thought to form at least in part from thermal erosion (Carr, 1974; Hulme, 1973; Head & Wilson, 1981), a process that should be generally enhanced on Venus (Head & Wilson, 1986).

PHOTO 14 is a typical terrestial channel formed from a volcano. In this Hawaiian photo, lava makes its way down to the sea following a slightly sinuous path. Unlike Venusian channels, their maximum width is around 30 m.

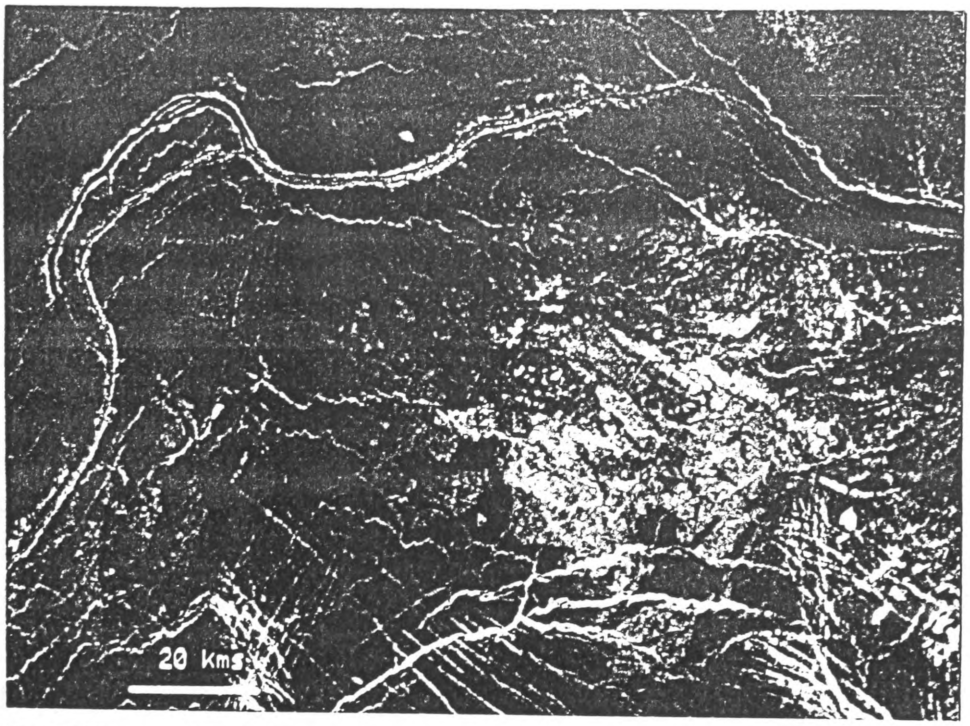


PHOTO 12
A mature meandering lava channel. **(F45N019)**

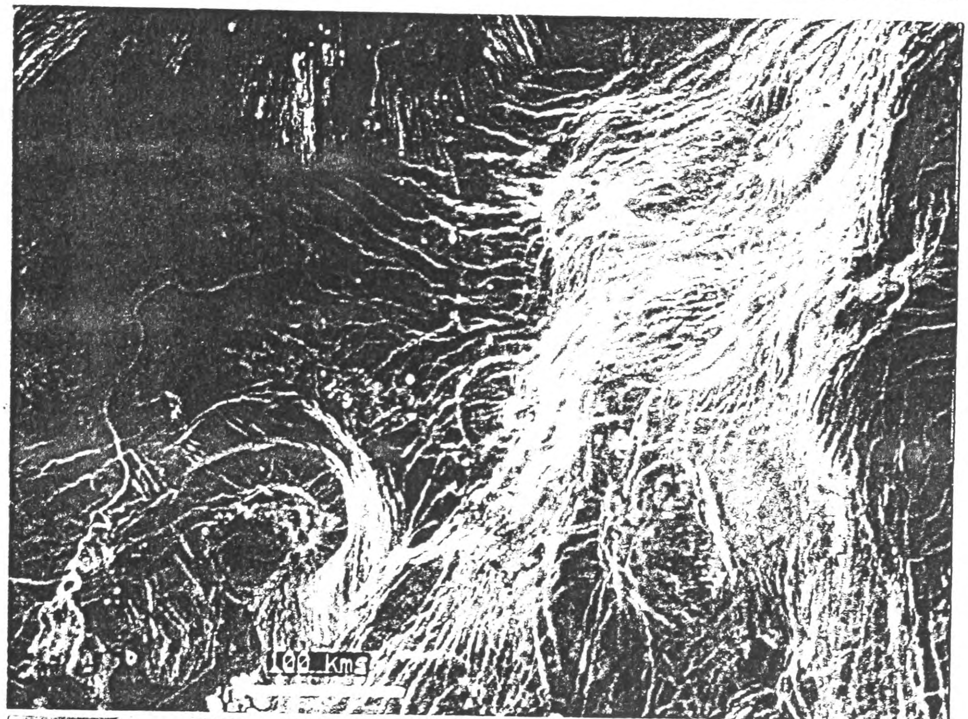


PHOTO 13
A larger scaled version of Photo 12.

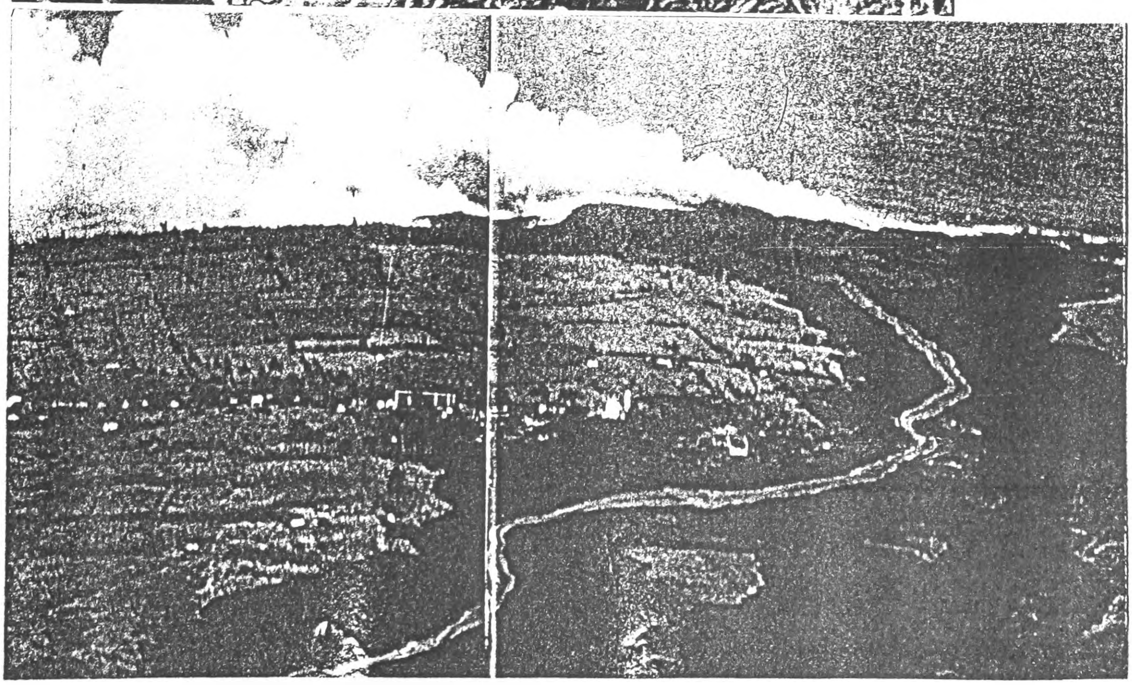


PHOTO 14
A typical terrestrial active lava channel.

The Venusian Topography and Channel Length

It is now known the Venusian surface is generally smoother than the other 3 terrestrial planets, with much less variation in altitude than is seen on the Earth. In fact, 60 percent of the Venusian surface is within 500 m of the planet's mean radius of 6052 km, and only 5 percent lies more than 2 km above it (Moore & Hunt, 1990).

Now, since the Venusian surface is relative smooth, than lava should at least be capable of flowing long distances (as was the case at Undara) assuming it can be sufficiently channelled and is mobile enough. This indeed appears to be the case on examining the large number of long channels on Venus. Also, if lava can flow considerable distances, in order to completely satisfy ourselves with explaining the long length of the lava rivers, we need only consider how a channel of lava can confine itself over such a long distance and remain fluid.

On the Earth, a new outflow of lava will act under gravity seeking the shortest possible path to a lower altitude. If the flow lasts some time, an excavation of the channel will result and leeves will form. As the flow progresses and the slope becomes more gentle, the channel will widen and become shallower.

Overflows along the course into surrounding areas are common and depend upon factors such as the volume of the flow, viscosity etc. If the volume of available lava is low, viscosity too high, too much cooling occurs on route, or the channel cannot confine the lava, then the lava river will be severely limited in length.

This is usually the case on the Earth, though lava cooling and the inability of the channel to confine the lava over long distances seem more often to be the reason.
On Venus, channels seem to confine themselves very well, over long distances. Photos 10, 11 and 13, show long sinuous streams with little variation in their widths and no clear indication of overflows.

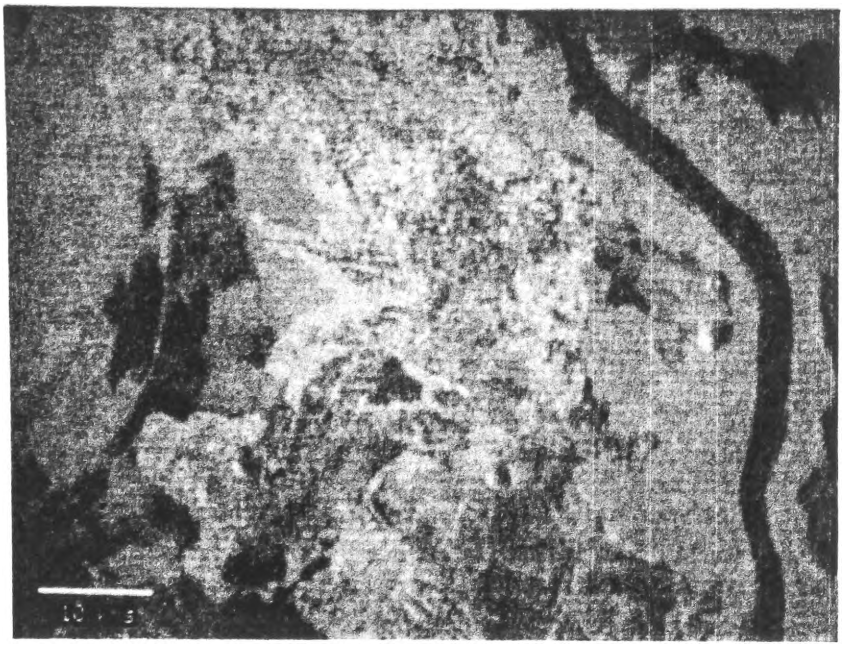
Quite clearly, the lower the number of overflows, the more lava that will be available to the channel and therefore, the longer the potential channel length. Further, this lack of overflows over considerable distances implies the lava is very fluid since the advancing flow is moving at such a rate that the volume behind it is relatively unhindered.

High channel confinement could also occur if a flow persisted over a long period of time or old pathways were reused leading to deep channel excavation. In photo 10, this lava channel has mostly drained exposing quite a deep excavation, the bottom of which reflects the radar beam in a similar way to the surroundings. This indicates the trench is quite rough, although very well defined. Photos 11 and 15, however, shows lava rivers which are dark in appearance, indicating they are smooth and therefore probably undrained. Even on the tight bends the lava seems to be well confined in these pictures.

<u>PHOTO 15</u> - F14S335

This photo seen on the next page is a dark lava channel, located southeast of Navka Planitia at 14.5 degrees south latitude and 335 degrees east longitude. The flow, over 30 km long and 2 to 3 km wide, has spilled out, at the top of the picture, from the main channel into the surrounding lowlands.

PHOTO 15
A dark lava channel.
(F14S335)



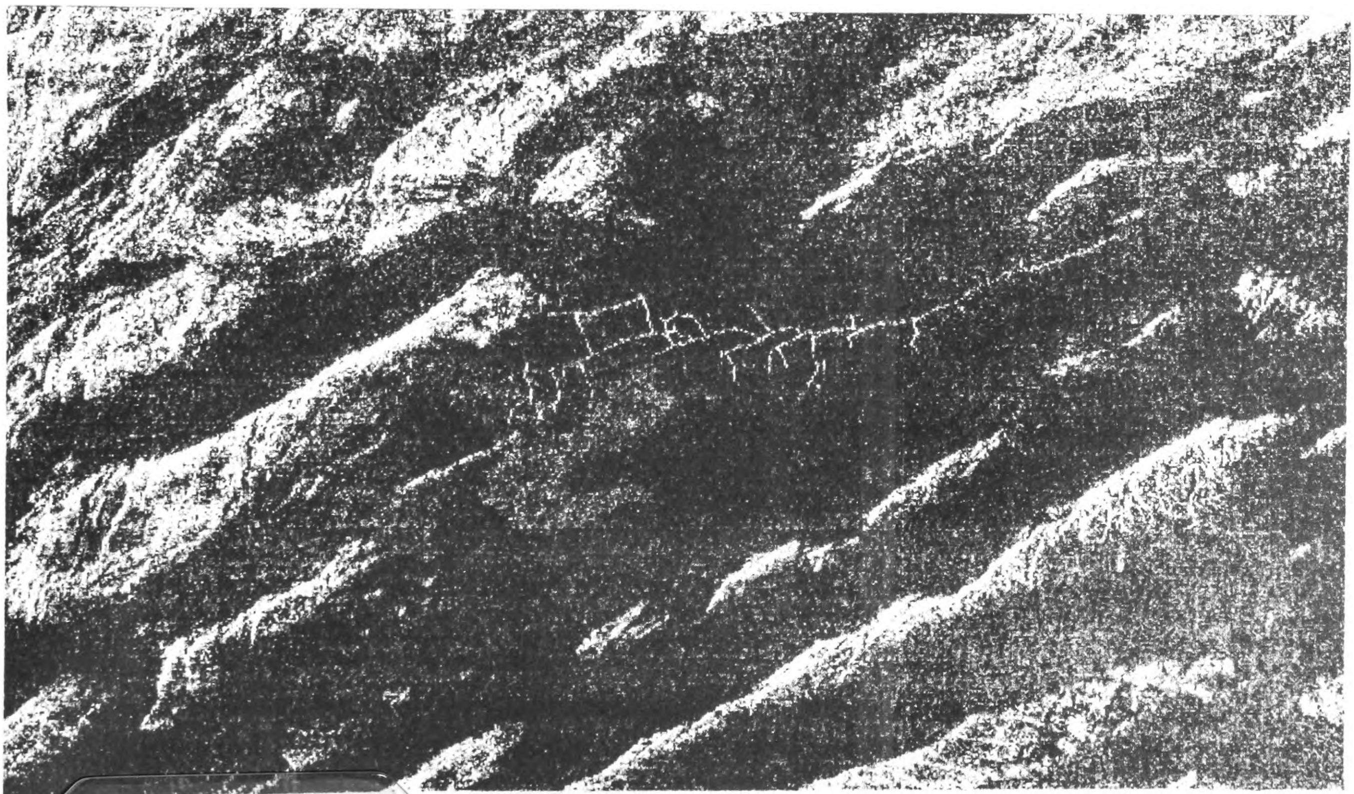
<u>PHOTO 16</u> - F00N070

A dendritic drainage pattern appears in this image located 0 degrees north latitude and 070 degrees east longitude.

This unusual 50-km-long network of cracks is found near the large equatorial "continent" of Aphrodite Terra.

One item definitely in short supply on blazing-hot Venus is water, so any channels seen on the surface must be the work of volcanic or tectonic processes - or, as here, both. A pattern of deep, intersecting fractures allowed molten rock to flood the surrounding terrain. When the eruption ended, magma drained back down the fractures, and the newly formed crust on top of them collapsed.

The fractures are visible to Magellan thanks to the rough, craggy jumbles that fill them.



Venusian Lavas

If Venusian lava is behaving differently to Earth-type lava, this is almost certainly due to its viscosity. Lava viscosity or mobility is known to depend chiefly on its chemical composition and temperature, but other factors affecting it include, pressure, gas content and density (MacDonald, 1972).

Temperature

A large amount of temperature information on Hawaiian lavas is available and some of this can be seen in the table below.

TABLE 1

SOME MEASURED TEMPERATURES OF ERUPTING MAGMAS

Volcano	Composition	Temperature(^{0}C)
Kilauea (1952-63)	tholeiitic basalt	1050-1190
Mt Etna (1970-75)	hawaiite	1050-1125
Paricutin (1944)	basaltic andesite	943-1057
Santa Maria (1940)	dacite	725
Mt St Helens	dacite	850
Longai	carbonatite	665

Hawaiian tholeiitic basalts approach the surface between about 1050^{0}C and 1200^{0}C (Table 1). For silicic magmas there is less data available because such eruptions have not frequently been observed this century. An optically determined temperature for the 1940 dacite dome of Santa Maria and a thermocouple measurement of the Mt St Helens 1980 dacite dome indicate substantially lower eruption temperatures than for basaltic lavas (Table 1).

Estimates of the typical eruption temperatures of the major magma types are given in Table 2.

Undara, as previously mentioned, erupted lava at temperatures between 1170^{0}C and 1220^{0}C.

TABLE 2

Summary of estimates of typical eruption temperatures for volcanic rocks (MacDonald, 1972).

Rock type	Temperature (^{0}C)
rhyolite	700 - 900
dacite	800 - 1100
andesite	950 - 1200
basalt	1000 -1200

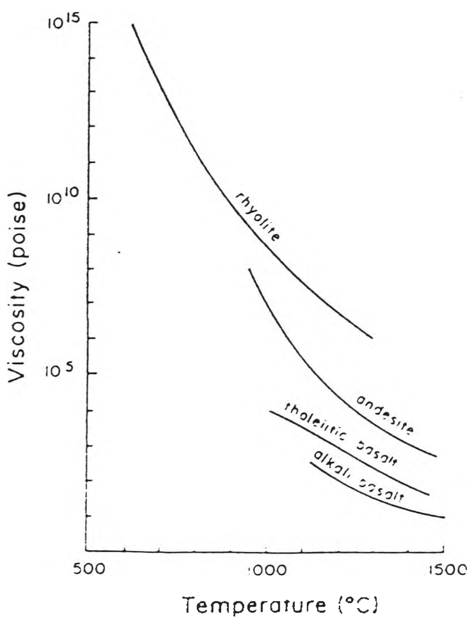
Viscosity is very dependent on the temperature of the magma (Figure 18). Both field and experimental data show that the viscosity of all magmas increases significantly on cooling (Williams & McBirney, 1979), partly due to crystallisation.

However, at equivalent temperatures and pressures different magmas have different viscosities, suggesting that compositional aspects are also important in determining their viscosities.

This close relationship between viscosity and temperature is vital in explaining Venusian lavas. The extent of the Venusian lava rivers in itself suggests very fluid lava exists on the surface of the planet. This idea is further enhanced by the high temperature (450^{0}C) known to prevail there. This means the longer it takes for the lava to cool down, the longer it will maintain its low viscosity, and hence the further it will flow. Further to this, if the lava was initially very fluid and effusion rate high, it may travel quite fast and therefore travel some distance and still maintain its mobility, losing little heat on its way. This appears to have been the case with the lava rivers we looked at in Photos 10, 11 and 13.

<u>FIGURE 18</u> TEMPERATURE AND VISCOSITY

Relationship between viscosity and temperature for some volcanic rocks (Williams & McBirney, 1979). The rhyolite was glassy or liquid through the entire temperature range. The rocks are the same as in Table 1.



Pressure

Experiments carried out in piston cylinder apparatus at supra-liquidus temperatures have shown that in natural and synthetic melts, the viscosity becomes lower with increasing pressure especially at high pressures.

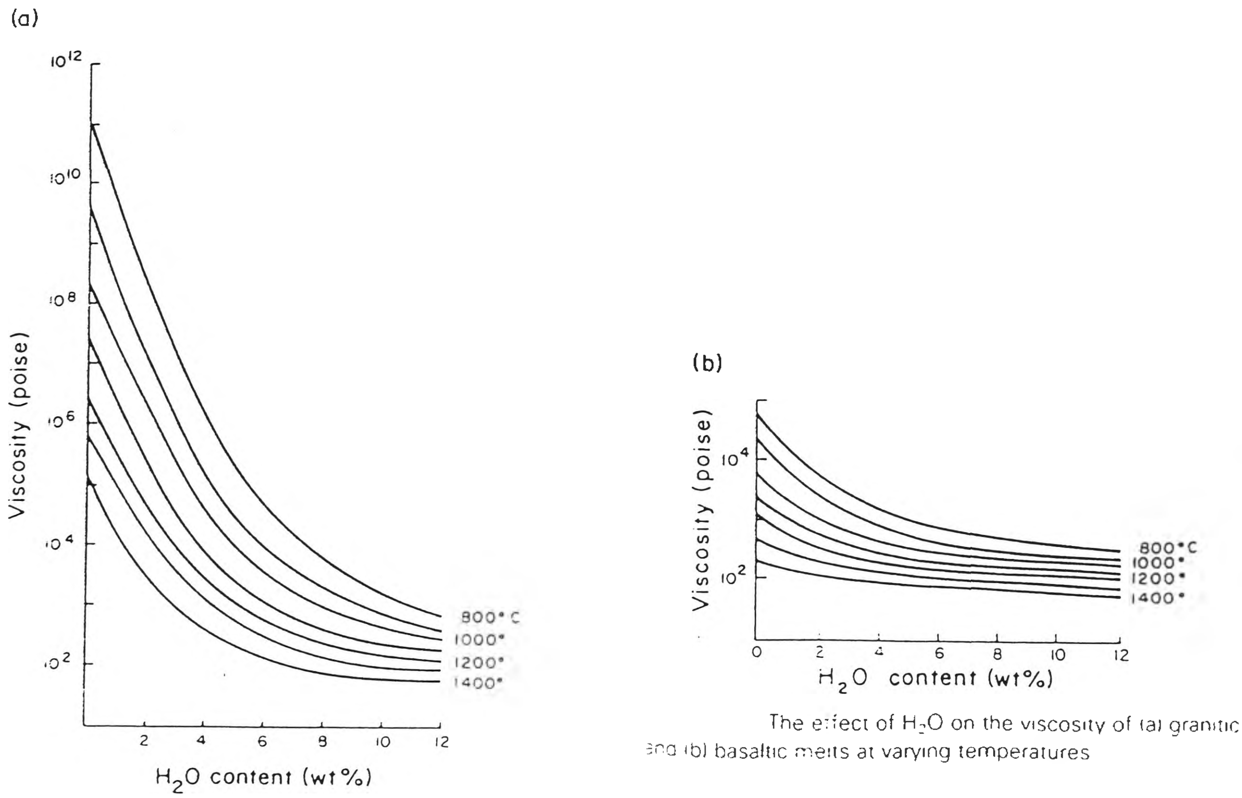
This pressure-viscosity relationship, like temperature, is also particularly revelant on Venus where the atmospheric pressure is about 90 times that of the Earth. It would appear conditions on Venus seem perfect for very low viscosity lava, hence lava rivers.

Volatile Content

Water dissolved in magmas has a marked effect on their viscosities as seen by Williams & McBirney 1979, McBirney & Murase 1970 (Figure 19).
At fixed temperatures the viscosity of a particular magma becomes lower with increasing water content, especially for more silicic magmas (Shaw, 1972). The solubility of water in magmas is controlled by temperature, pressure and the presence of other volatiles.

FIGURE 19 **WATER AND VISCOSITY** (Williams & McBirney, 1979)

the effect of H_2O on the viscosity of
a) granitic and b) basaltic melts at varying temperatures



The effect of H_2O on the viscosity of (a) granitic and (b) basaltic melts at varying temperatures

Although, water is not thought to exist on the surface of Venus (water can only remain liquid if its temperature is between 0^0C and 374^0C), it may exist below the surface. If it does exist and mixes with the magma, a lower viscosity magma will result.

The exact effects of other volatiles is poorly known, being dependent on their solubilities and abundances. Peralkaline rocks have Cl and F contents which are thought to considerably reduce viscosities and yield strengths of magmas of these compositions.

Until recently (see Table 1), fluid lava existing at temperatures much below 800^0C was unheard of, but an expedition to Tanzania, in Africa, changed this belief. The volcano, Longai, was expelling a quite mobile lava river, which melted at only 500^0C, that is, before it turned red-hot. This is indeed around the surface temperature of Venus.

This **carbonatite** lava was black in colour and looked like hot mud, but at night glowed red-hot. The resulting lava river was only small but had quite a meander and formed a lava pool in one section.

Carbonatite is widespread and locally abundant on Earth but is rare compared to basaltic and many other silicate magmas. Carbonatite volcanism can be found in certain shield areas, on hotspots, and along the East African Rift. Carbonite is mantle-derived and is almost exclusively associated with alkaline mafic and ultramafic silicate volcanic rocks such as alkali basalt, nephelinite and kimberlite. This fact is interesting because Venusian lavas tend to be highly alkaline, particularly from samples analysed by the Venera 13 spaceprobe, which closely resembles olivine nephelinite (Baker et al, 1992).

Quite clearly, a lava river on Venus like the one in Tanzania, would flow quite a considerable distance, and it would not cool at all below the critical viscosity-temperature point. This means the maximum length it could attain, assuming it remained channelled, would be determined only by the supply of lava at its source. Although the surface of Venus, in most cases can be regarded as being gently sloping, very fluid lavas, such as those in Hawaii, have attained the considerable speed of 30 or 40 km per hour on gentle slopes (MacDonald, 1972).

Thus, if a flow were to stay mobile for say 10 hours or more, not unreasonable under Venusian conditions as discussed, a lava river may attain a length in excess of 400 km. Again, not unreasonable, assuming there was an adequate supply of magma. This long flow period will also lead to channel excavation.

Lastly, if there are some very fluid lava on the surface of Venus, which certainly seems to be the case, the lava would need to be low in silica, that is, basaltic lava. In these sort of lavas, dissolved gases escape readily and typically extrude quietly from fissures and fractures (MacDonald, 1972).

Although fissure eruptions are beyond the scope of this thesis, it should be mentioned that if they are widespread on Venus, like the Earth, they would mask or hide with their lava flows, many areas such as crater chains or indentations.

In the next section, various photos would seem to bear out this point.

Summary and Conclusion

Since conditions on Venus differ considerably from that of the Earth, it is reasonable to expect that magma upon reaching the surface may behave unlike Earth-type lavas.

There are several possibilities for low-viscosity, channel-forming fluids on Venus, including ultramafic or highly alkaline mafic silicates, carbonatite, and sulphur. The last two are attractive since they have very low melting points and water-like viscosities and would readily explain the great lengths, fluvial-like aspects, and longitudinal uniformity of channels. Ultramafic or alkaline mafic silicate lavas are attractive since the surface as reported by the Venera and Vega landers is composed primarily of mafic silicates, and highly potassic rocks occur at two of several landing sites.

The higher temperature and pressure present on Venus set the scene for some quite fluid eruptions, and as was the case with Undara, a favourable topography and high output of magma will lead to extensive lava flows. Photos and measurements appear to bear this out and show many lava channels longer and wider than any found here on the Earth.

As well these channels may have drained when very fluid lava passed through them or somehow became blocked resulting in relatively smooth lava upon cooling and only a partial emptying of the channel. **On Venus lava in lava channels seems to behave like water does in watercourses on the Earth.**

Finally, although lava channels are relatively common they are not a dominant feature, as are the coronae and domes, in the volcanic areas. These domes and other features show that very viscous lavas are also quite common for reasons which are as yet unclear.

3.2.2 Type B - Crater Chains

These are a series of craters which, in Magellan images, appear usually unconnected, and have an irregular roundish appearance. They are referred to as 'chains' because they seem to be linked and large numbers of them together give a 'chain like' appearance (Photo 17).

In the region of Venus covered (approximately 20%), 260 chains were studied and these data are found in **Appendix A (Table 1).** Chain length may be as small as a few km (2.2 km) or as large as 220 km, which was the longest, but most are around 25 km in length. The width of these chains usually varied somewhat, so an average value of the chain was recorded. The largest average chain width was over 2 km, though these were rare, and they ranged all the way down to the limit of resolution which was 120 m, the average being about 552 m. The number of craters in a chain varied considerably from only 2 to about 60, the average being 15.8.

RESULTS

Appendix A (Table 1) also shows other details which were noted and recorded besides statistics when data was collected. These include :

1) whether or not the chains appeared to follow faults. If no faults were seen than a 'dash' was recorded.

2) whether a chain was curved or not along its length was also recorded, as well as whether it was parallel to other chains, if other chains were in the vicinity.

The following points become evident from the table in Appendix A (Table 1).

* There is considerable variation in number, length and diameter of the crater chains.

* Most images with crater chains show evidence of faults or fractures (222 out of 260 crater chains). Out of these 222 chains, 96 appear to lie on faults or fractures, 100 do not, and 26 simply head in the same direction.

* The vast number of crater chains are very straight (224 out of 260), 15 may be regarded as slightly curved, while 17 have a definite curve, and 4 may be best described as bent-shaped.

* Crater chains usually occur in groups and in the vast majority of cases, when other chains are present, they are parallel to one another.

Relationships (or in some cases the lack of them) can be seen from the tables and charts also in Appendix A.

Chart 1 shows the result when all the crater chains studied are arranged in order, from smallest to largest in length, and then plotted against their corresponding diameters. The random pattern shows clearly no relationship exists between average crater chain diameter and their length.

Chart 2 shows there is a relationship between the length of a crater chain and the number of craters in that chain. In this chart, the chains were arranged from the smallest number of craters in the chain to those with the largest number of craters. As crater chain length increased, the number of craters in these chains also increased.

The number of chains having a particular diameter can be seen from *table 2*and the corresponding graph from ***chart 3*** They show the diameters of the chains jump suddenly up to 200 m, peak in the 301-400 range, then gradually taper off up to the 1500 m mark. Thus, there is no even distribution.

Table 3 shows the number of crater chains having a particular length and the corresponding graph is shown in chart 4. A preferred length between 10 and 20 km is seen followed by a sharp drop, with the familiar tapering off up to around 70 or 80 km.

DISCUSSION OF RESULTS

The above statistics show there is a considerable range in values for most aspects of the crater chains. The considerable variation in length goes hand in hand with the variation in crater number as one would expect, especially considering the expected correlation between chain length and number. Simply put, since the longer chains do not have correspondingly larger crater diameters, then, there must be more of them making up the chain.

In regard to crater diameters, there seem to be few very big or very small sized craters. However, the steep increase in numbers of chains having diameters greater than 200 m is not matched by the tapering tail on the upper end of the scale. The bump in the 1001 to 1100 m diameter class would appear to be a statistical rather than a physical anomaly. Also, since some craters observed were barely visible, that is, close to the limit of resolution (120 m), one would logically expect some craters to have diameters less than this limit.

Thus, the lower limit for crater chain diameter is indeterminate. The centre section, that is, those having diameters between 200 and 1100 m comprise about 90% of the group and this spread would seem to be due to variable factors in their mode of formation.

It must be also noted that crater diameter (as recorded in the tables) means average chain diameter of a particular chain. This was necessary since some chains showed considerable variation in individual crater diameters.

As for the lengths of the crater chains, much can be said which was similar to that of the crater diameters. There were very few exceptionally long chains but a good number of smaller ones. The vast majority being less than 60 km in length but again with a reasonable spread around the median in value.

INTREPRETATION OF RESULTS

The results show we have a series of craters varying in number from 2 to over 60, but averaging 16 lying in chains. The vast majority of chains are **straight**. Their length can be anything from 2 to 220 km, but most are between 10 to 30 km. Individual craters may have a diameter up to about 2 km.

Considering this information (Appendix A) collected from Venus and applying it to known Earth structures, at the same time disregarding size, I can only conclude that these craters must be collapse features. Furthermore, they must be ***pit craters,*** collapsed ***lava tubes*** or some sort of combination of the two. Craters formed from gas explosions cannot explain these results, for reasons that will be discussed shortly.

I believe my research shows that not all of these collapse features can be explained as pit craters, and in fact, a significant number may indeed be collapsed lava tubes.

PIT CRATERS OR LAVA TUBES ?

From an aerial viewpoint, terrestial pit craters are easily seen (Figures 20 and 21). They are found in volcanic areas, range in diameter from about 5 m to around 1600 m or so, and in depth from several metres to more than 300 m. They are usually roughly circular or oval in shape, except when they overlap, in which case, they can resemble a figure eight.

In Hawaii along the rift zones of the shield volcanoes Kilauea and Mauna, for example, nearly circular craters perforate the surface of the volcano without any surrounding debris cone. There is a very small amount of phreatic explosion debris scattered near the edges of a few of these craters, but most have none, whatsoever (MacDonald, 1972).

Certainly, these craters could not have been formed by explosion, since the surrounding debris, where it is found, only makes up a tiny fraction of the volume of the crater. Thus, they could only have resulted from the sinking in of parts of the volcano. A line of 12 pit craters is followed by the Chain of Craters Road in Hawaii Volcanoes National Park.

In their early stages pit craters have walls that are are nearly vertical, but their rims soon begin to fray and as a result fallen rock fragments accumulate as great sloping banks (taluses) against the foot of the walls (MacDonald, 1972).

FIGURE 20 KILAUEA PIT CRATERS

Pit craters formed by collapse of the surface on the southwest rift zone of Kilauea Volcano. The nearer crater is approximately 50 metres across. (U.S. Geological Survey photo by G.A. MacDonald).

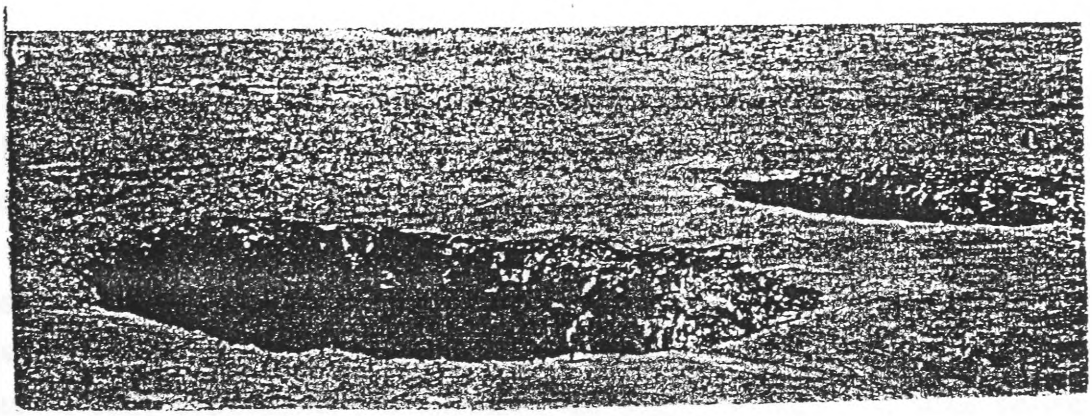
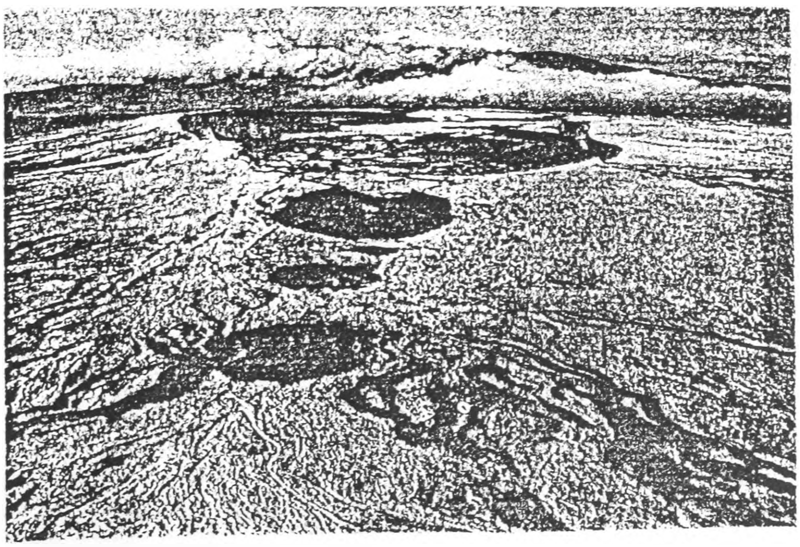


FIGURE 21 MAUNA LOA PIT CRATERS

The summit of the shield volcano of Mauna Loa, Hawaii, with Mauna Lao in the background. In the foreground are three pit craters along the upper end of the southwest rift zone of the volcano, and behind them is Mokuaweoweo Caldera. The mountain is covered with a light fall of snow. (Photo by U.S. Air Force).



Several pit craters in Hawaii were formed in historic times, but two were seen immediately after they first formed. One of these is the Devil's Throat, near the Chain of Craters Road in Hawaii Volcanoes National Park and the other is Lua Nii (MacDonald & Eaton, 1955), formed on the east rift Zone of Kilauea 30 km east of the summit of the mountain during the 1955 eruption. Initially, both had openings only about 8 or 10 m across, their craters becoming larger downwards, so that the walls were overhanging. Collapse of the upperpart soon transformed the walls to vertical.

From a purely observational point of view, disregarding size, it is difficult to distinguish between pit craters and the skylights of collapsed lava tubes on the Earth. They can have similar dimensions and shape, both have craters that can run in a line forming a chain and both are the result of collapses.

This task becomes even more difficult on Venus where there are so many more unknowns so that a clear distinction between pit craters and collapsed lava tubes becomes virtually impossible. For example, the slight difference in scale between the two on the Earth becomes meaningless on Venus where everything seems to be scaled differently.

However, I believe in some cases this distinction can be made, not by just appearance or size but by looking at more subtler clues such as, how they may have formed, as well as, where they are located, what's in surrounding areas and the type of terrain they are found in.

Recall that the narrow depressions associated with these collapses at Undara attained a maximum width of about 50 m. Since Magellan images have a resolution around 120 m, then if we are seeing collapses associated with lava tubes, they must be on a much grander scale. But, then again, if the lava channels are so very much larger on Venus then the Earth, why can't lava tubes be also?

Clearly, if collapsed Venusian lava tubes are of the same dimensions as their terrestrial counterparts they will not be seen by Magellan radar.

However, because we may be willing to accept the possibility of incredibly large lava tubes doesn't mean we are actually seeing collapsed ones.

Before we draw any conclusions lets firstly examine some photos of possible candidates of pit craters and lava tubes.

PHOTO 17 - **F60N005** on the next page shows a depression which appears quite fresh and narrows down to a crater chain. The craters are quite distinct, vary in size and seem to come to a sudden stop. The upper section appears slightly grooved indicating lava has flowed along the channel, probably towards the centre (SE)- **(see diagram below)**. This seems consistent with lava tubes which are known to have collapses whose size usually increases upslope because the tube below the surface is closer to the surface.

Hence, one may interpret this picture as being the result of some sort of lava channel flowing roughly to the southeast, and either part of the tube didn't roof over or has completely collapsed carrying away the collapsed material. The abrupt end of the chain may mean the lava drained away or the channel has continued below the surface. There is no evidence of part of the chain having been flooded by other lava flows. This picture would appear to be inconsistent with a pit crater explanation since pit craters usually have deeper connections. This channel is located near 60 degrees north latitude and 005 degrees longitude which is in Ishtar Terra, south of Maxwell Montes.

PHOTO 18 - **F05S076** on the following page appears to be a series of **grabens**. The larger one (centre) is over 300 km long in entirety, which appears to narrow into a short chain at the centre then continues on again until it again narrows into another chain. These collapses probably occured when lava invaded the graben and then withdrew as indicated by the smooth floor and lack of etching as in the previous photo. A clear flooding of part of the channel from another channel has occurred just right of center. This image is near 5 degrees south latitude and 76 degrees east longitude in the Aphrodite Terra region.

Lava Direction Through A Channel

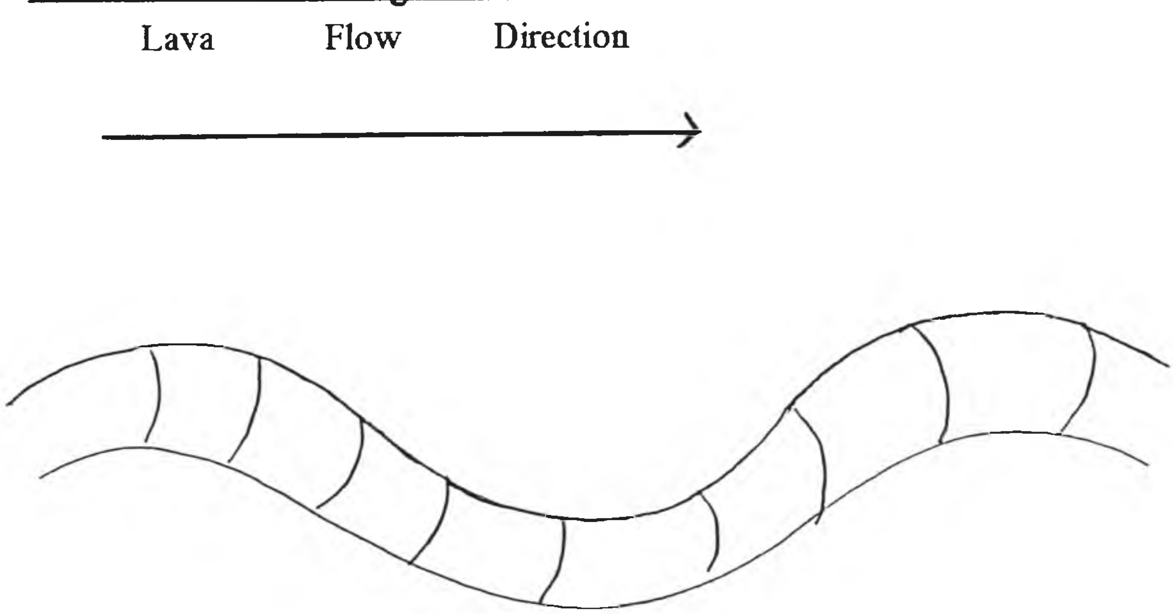


PHOTO 17
A crater chain associated depression.
(F60N005)

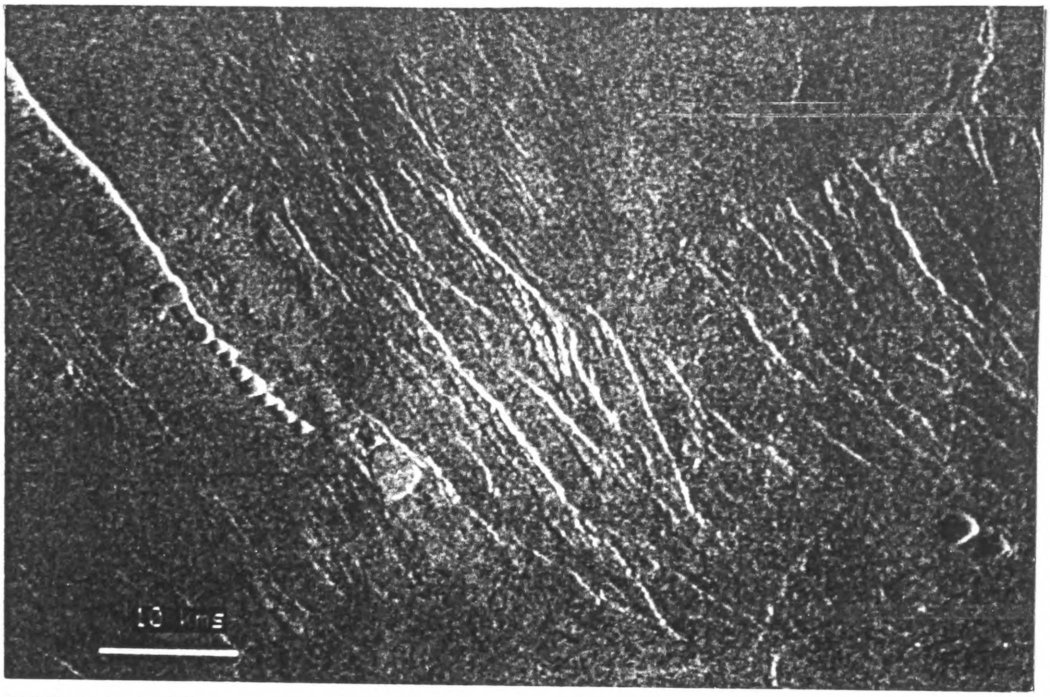


PHOTO 18
A long channel with a mid-centre collapse.
(F05S076)

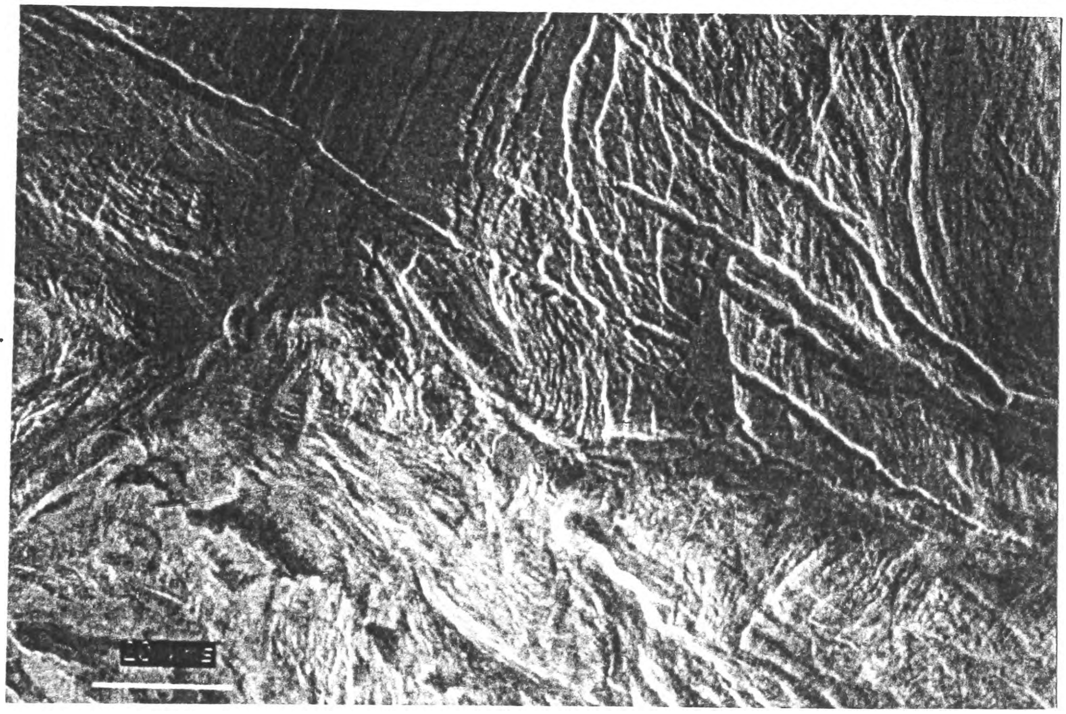


PHOTO 19
A probable pit crater chain.
(F20S121)

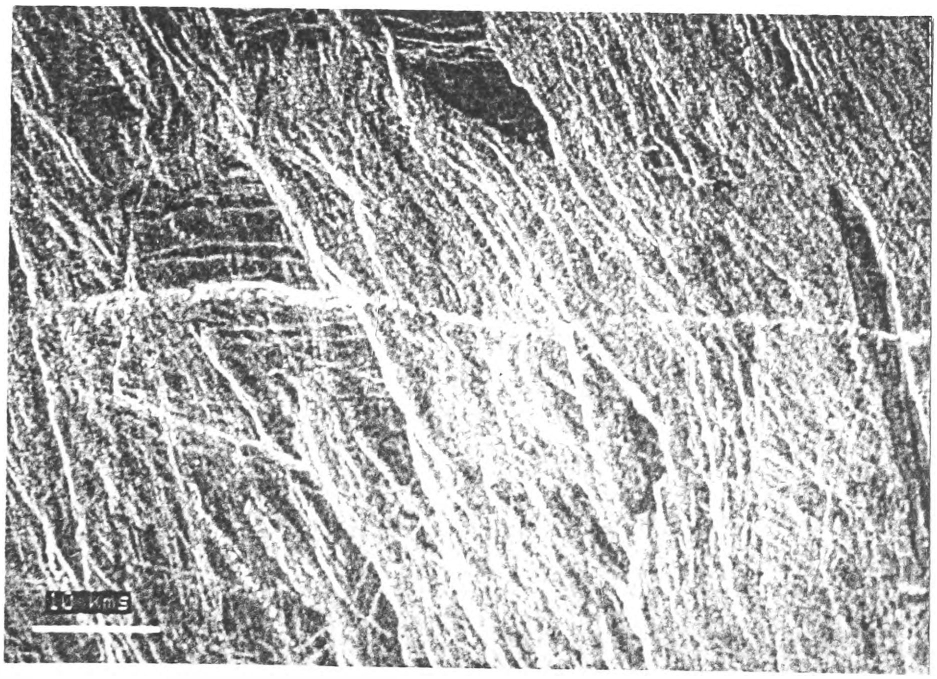


PHOTO 19 - F20S121 on the previous page shows a very long chain which cuts across an indentation. This seems more consistent with a series of pit craters than a collapsed lava tube. Notice the chain cuts across the indentation to the right meaning it is younger than it. It is located at 20 degrees south latitude and 121 degrees east longitude in southern Aphrodite.

PHOTOS 20 and 21 - F60N355 show a large number of parallel linear to scalloped troughs and pit chains known as Rangrin Fossae. Lava has flowed through the channels cutting the radar-dark volcanic deposits of Lakshmi Planum because Photo 21 (a close-up view of Photo 20) reveals the flow direction, as seen by the etching, which is towards the bottom right of the picture in the direction of the volcano. Other photos eg. photo 33 and 17, also tend to indicate these channels flow in this way. The scale reveals that the channels actually stop well short, about 70 km, from the volcano's central caldera. A possible topographical interpretation and discussion can be found on the next page.

Photo 21, which suffers from overlay, also reveals a number of crater chains running alongside the channels. It would seem that these craters window deeper sub-surface structures or chambers which may later open up increasing the size and number of these channels. Thus, it would seem inconceivable that these channels are or were lava tubes. They may be explained as gigantic channels, some 8 km wide, which once carried huge volumes of lava which either 'gouged out' the surface, or relatively shallow sub-surface channels (not lava tubes) which collapsed. What happened to this lava is unclear but it probably drained below the surface.

These channels seem quite deep and appear in a pristine state. They are located at 60 degrees north latitude and 355 degrees east longitude which is just southwest of Maxwell Montes.

A Possible Topographical Interpretation of Photo 20

The channel-like troughs in photos 20 & 21 do not appear to originate from the caldera, right of centre in photo 20, if the topographical interpretation below is correct. This interpretation is regarded as being the most probable (Kaula et al, 1992). These troughs are oriented at large angles to the plateau edge, trending N30^0-65^{0}W (in contrast to the troughs which parallel the northern border of Lakshmi).

These troughs occur in a region extending from 337^{0}E to 2^{0}E and south of about 64^{0}N to the edge of Lakshmi. They are 75-270 km in length and taper in width to the north. Widths range from 8 km to 600 m. Most of the troughs curve to the east near the edge of the plateau with their spacing varying from 1-10 km. The origin of some of these troughs is thought by Kaula et al. to be related to dyke intrusion and eruption of lavas.

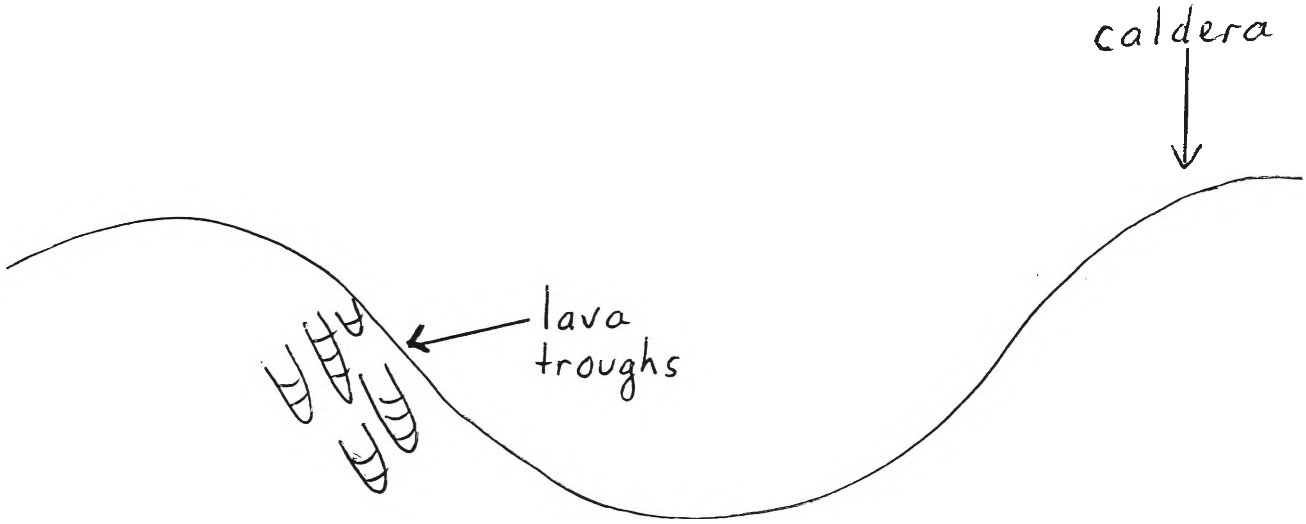


PHOTO 20
Parallel lava
channels with
a nearby
volcano.
(F60N355)

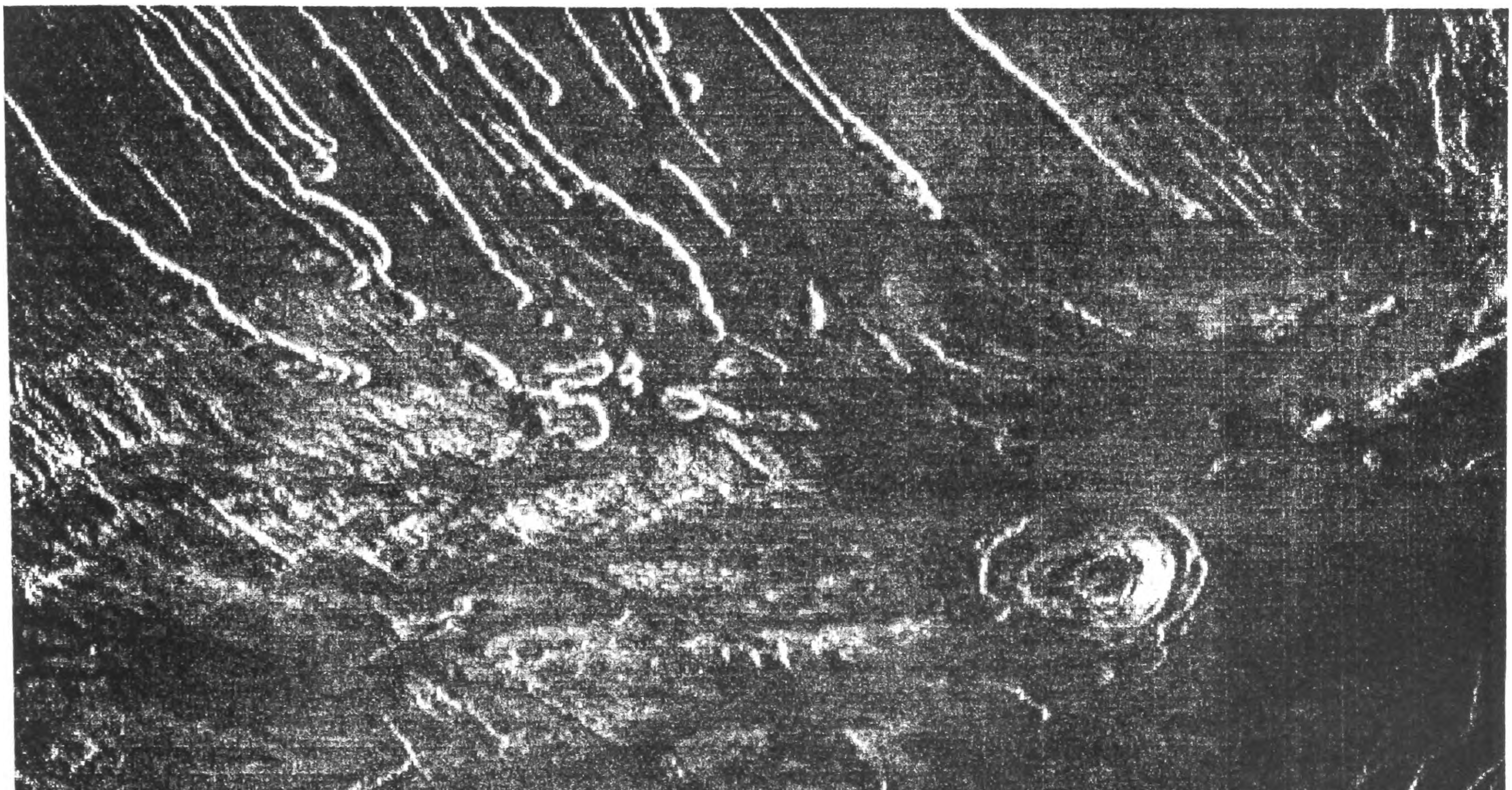


PHOTO 21
A close-up view. Notice the channel etching.

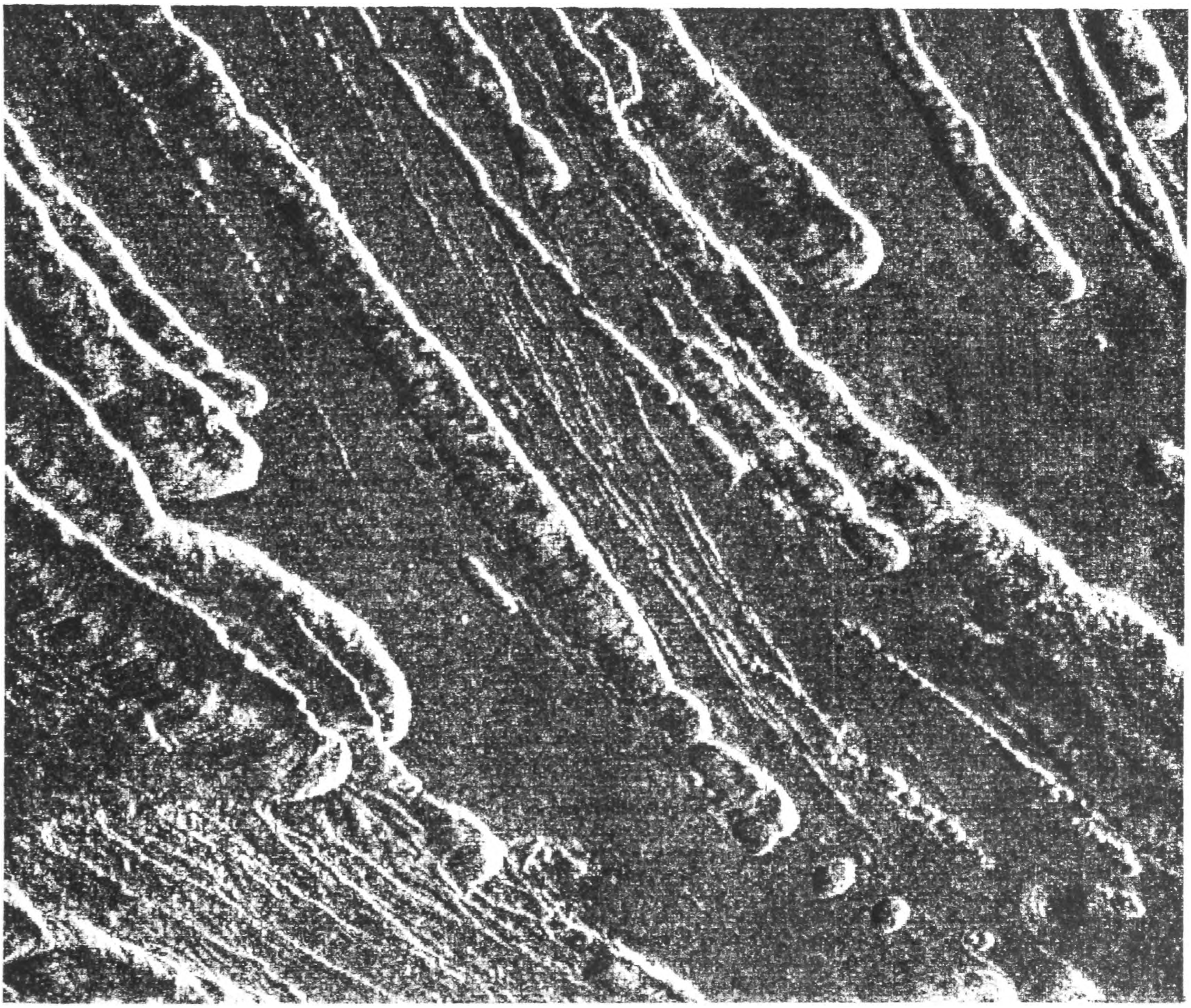
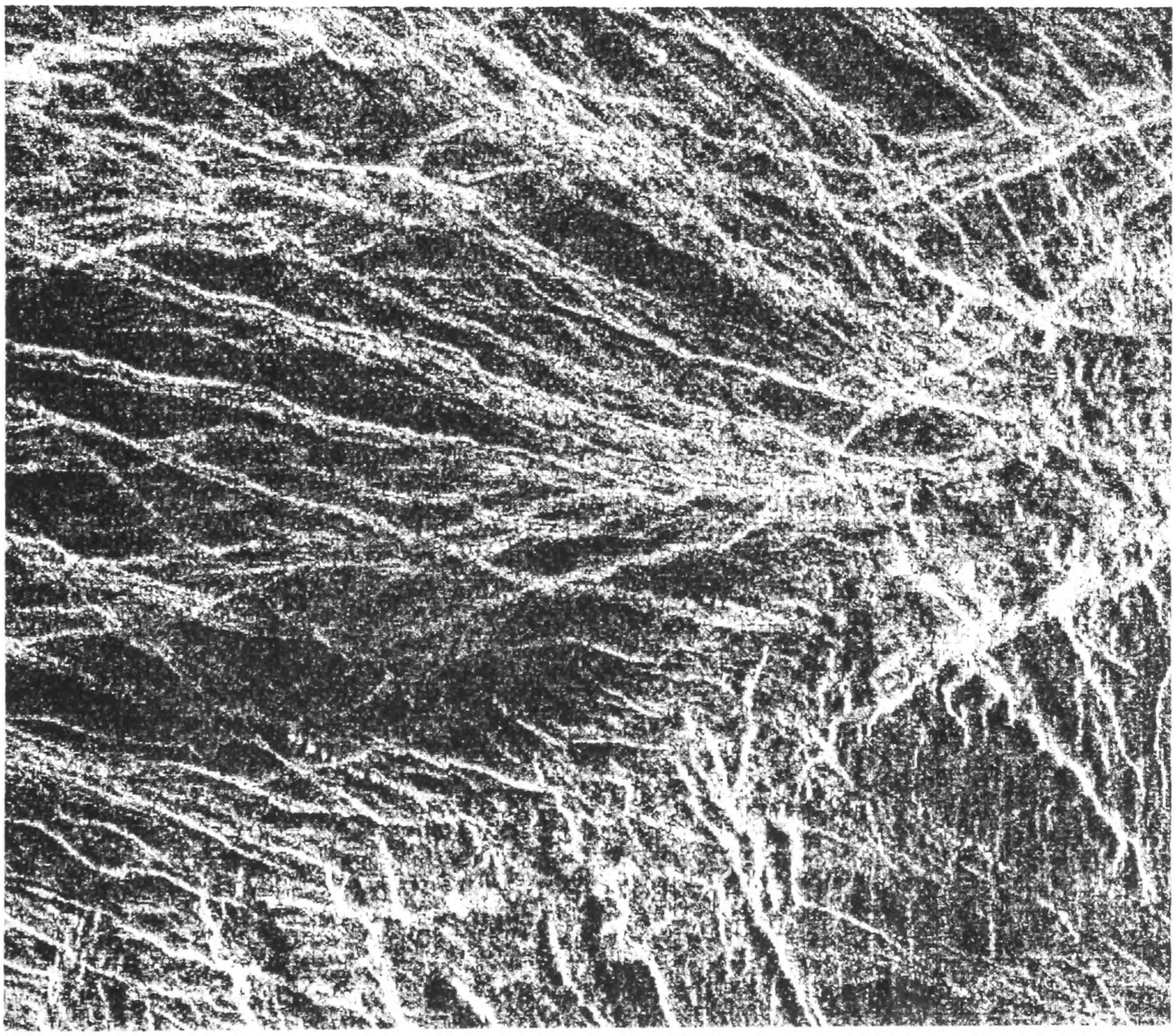


PHOTO 22
An usual image showing a number of features all starting from the same point near the centre. **(F20S121).**



The photos on the following pages seem to be definite pit crater candidates

PHOTO 23 - **F00N194** on the next page is a good example of what we expect terrestial pit craters to look like. A large number are arranged mostly in a radial pattern on the flanks of the Venusian volcano which is situated upper left of the centre of the picture. No obvious faults are present, although, they could be masked by the numerous lava flows in the area. Most of the craters are roundish or oval in appearance but some are elongated. The largest being over a km in diameter. A number of lava flows are also present. This image is located in a highland region in eastern Aphrodite Terra near Maat Mons, a volcanic region. The coordinates are 0 degrees north latitude and 194 degrees longitude.

PHOTO 24 - **F45S019** shows a series of craters running along a fracture near what appears to be a volcano (lower left). It seems that stresses caused by magma below the surface made the surface stretch resulting in a series of concentric fractures, some of which later collapsed (gravity slumps). These appear similar to pit craters rather than lava tubes. The image is near 45 degrees south latitude and 019 degrees longitude in the Lavina Planita region.

PHOTO 25 is a similar feature to Photo 24 and is found in the same vicinity, it probably also formed in a similar manner. Notice the almost perpendicular intersecting fractures (chains).

PHOTO 23
This shows a
number of
pit craters
located near
a Venusian
volcano.
(F00N194)

20 km

PHOTO 24
Fracture related pit craters.
(F45S019)

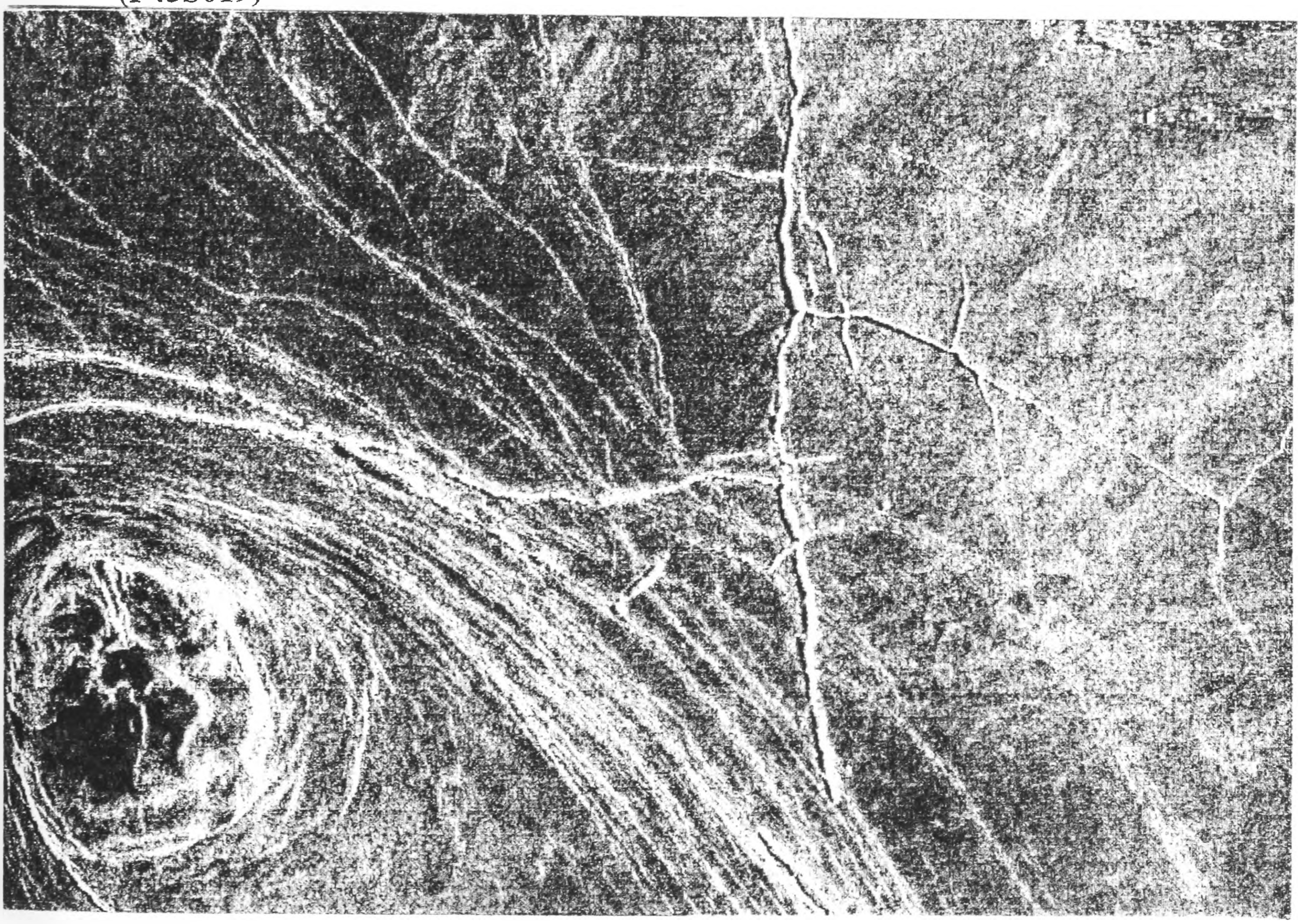


PHOTO 25
Intersecting concentric fractures. Notice the curve-like shape.

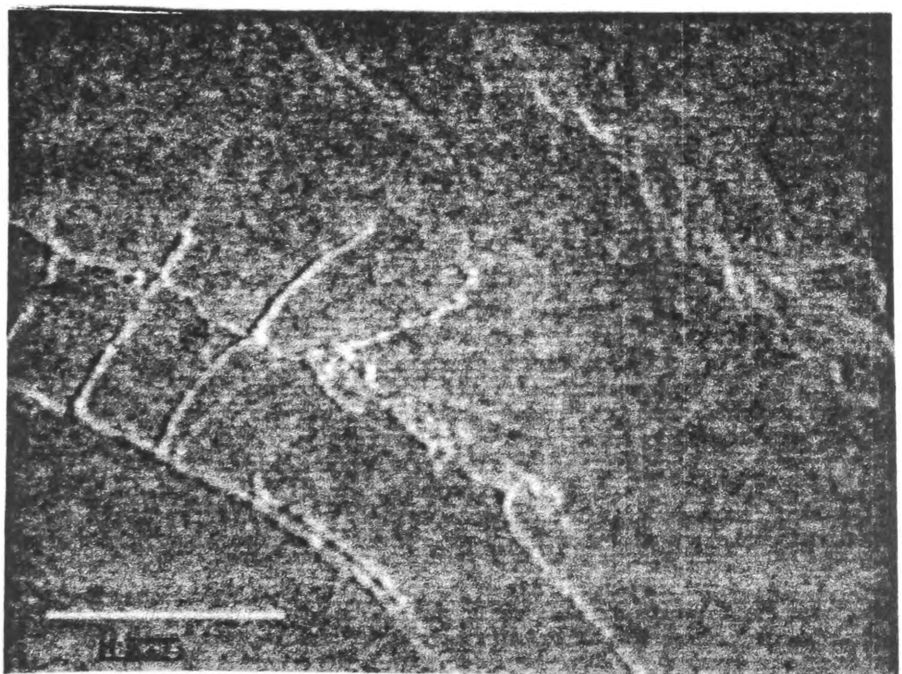


PHOTO 26 - F40N018 on the next page shows an excellent example of a ring fracture (circular chain of craters) around a Venusian volcanic complex. Clearly, these are a series of pit craters formed by stresses below the surface of the volcano related to the magma in the magma chamber (see Figure 22A). A larger number of craters in a ring-like pattern are seen.

This picture is near 40 degrees north latitude and 018 degrees longitude in a relatively low lying region.

FIGURE 22A is an illustration of how ring fractures occur (MacDonald, 1972). Barely a few km beneath the Earth's surface, a huge magma reservoir gradually undermines and domes the crust. When the root of the reservoir breaks, magma immediately erupts in a tremendous Plinian explosion, which creates a ring of fractures. The expanding gases drive a turbulent, ground-hugging froth of pumice and ash out from the ring fracture, obliterating the entire landscape : the root subsequently collapses to form a caldera. Notice the concentric fractures, these were also seen in Photos 24, 25 and 26, however, no dust, ash or gases were evident in the Venusian photos.

PHOTO 27 again shows some intersecting pit craters of various sizes, some of which follow quite complex patterns. Notice also the large number of criss-crossing fractures with the pit craters aligning themselves with this unusual pattern. Again, a pit crater, rather than a collapsed lava tube explanation would tend to fit these observations. This area is found in the vicinity of Photo 26.

This region has features in common with some of those found on Mars, namely Labyrinthus Noctis. This will be discussed later.

PHOTO 26
Ring fractures around a Venusian volcano.
(F40N018)

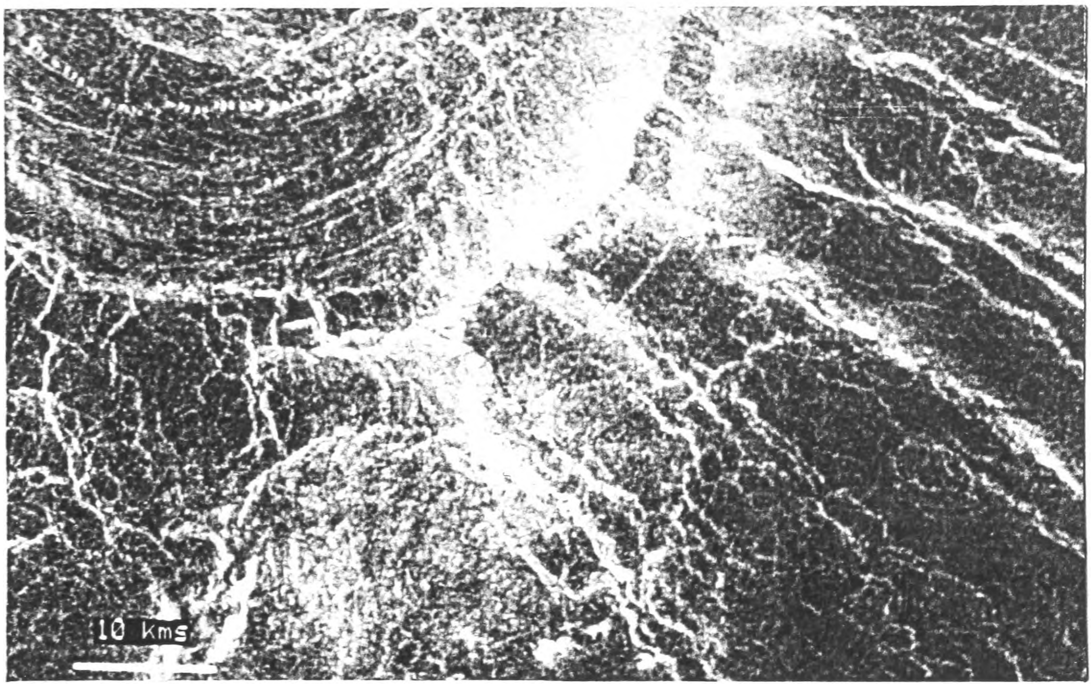


FIGURE 22A
Illustration of how ring fractures occur.

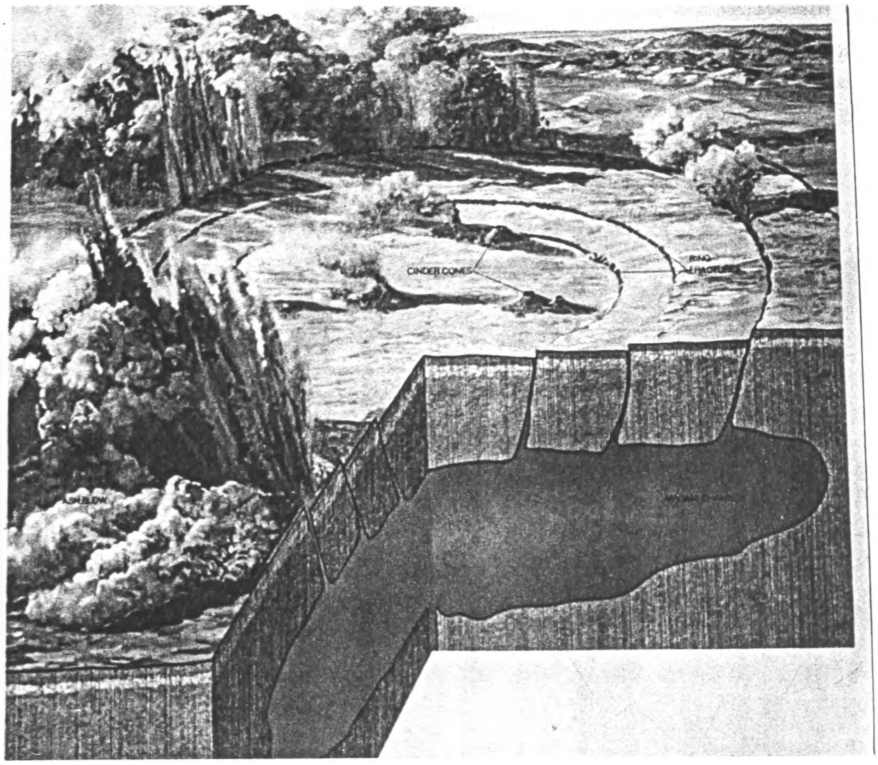
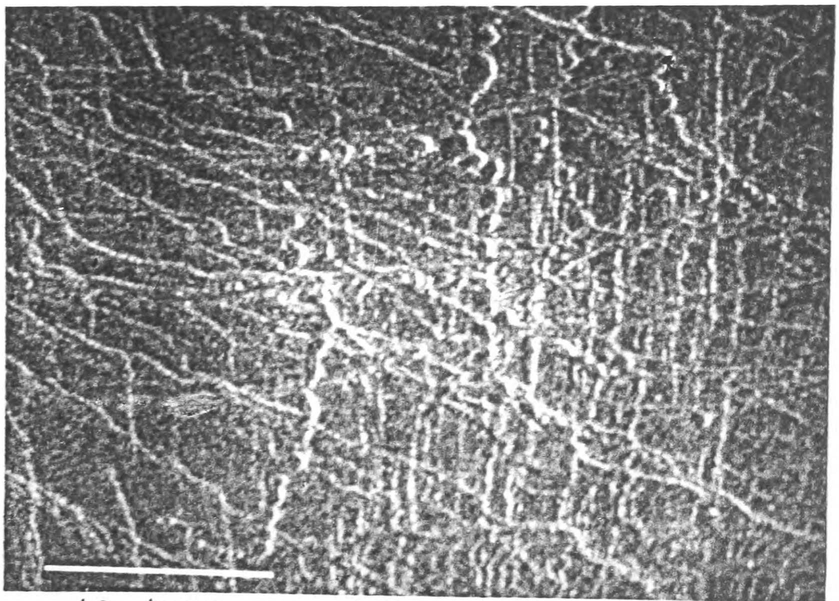


PHOTO 27
A pattern of intersecting fracture-related craters.



10 kms

PHOTO 28 - F60S355 on the next page illustrates how a number of features on Venus can be found in the same area. An ancient impact crater, named Alcott, about 60 km wide is partly visible in the centre, which has been mostly filled in with lava from the volcanoes on the left. Several collapse features are also visible, probably caused when subsurface magma drained along surface fractures, allowing the overlying surface to collapse. A giant lava tube, called Nike Fossae, is also seen just to the left of the impact crater.

Located near 60 degrees south latitude and 355 degrees east longitude in the Lada Terra region.

PHOTO 29 - F60S355 this is an enlargement of a section of the previous photo showing the extent and shape of some of the collapsed features. Notice their trailing/connecting crater chains. Again, these craters appear to be pit craters since they connect down to subsurface chambers. The dark section is radar shadow indicating the trenches are deep and the picture scale shows they are certainly huge in size. Two of the collapses appear to be overlapping but this may be explained as radar 'layover'.

These features are located near 60 degrees south latitude and 355 degrees east longitude in the Lise Meitner region.

PHOTO 30 - F00N076 shows a chain of craters running along a long curving fracture in the centre of the picture. Another apparent fracture further up, left of centre, has opened into a number of large pit-like craters or indentations. A couple of pancake-like structures can also be seen near the centre indicating some quite viscous lava flows have occurred some time in the past. One of these pancakes has a pit/tube passing through it.

This region is situated on the equator at longitude 076 degrees east on the western side of Aphrodite Terra.

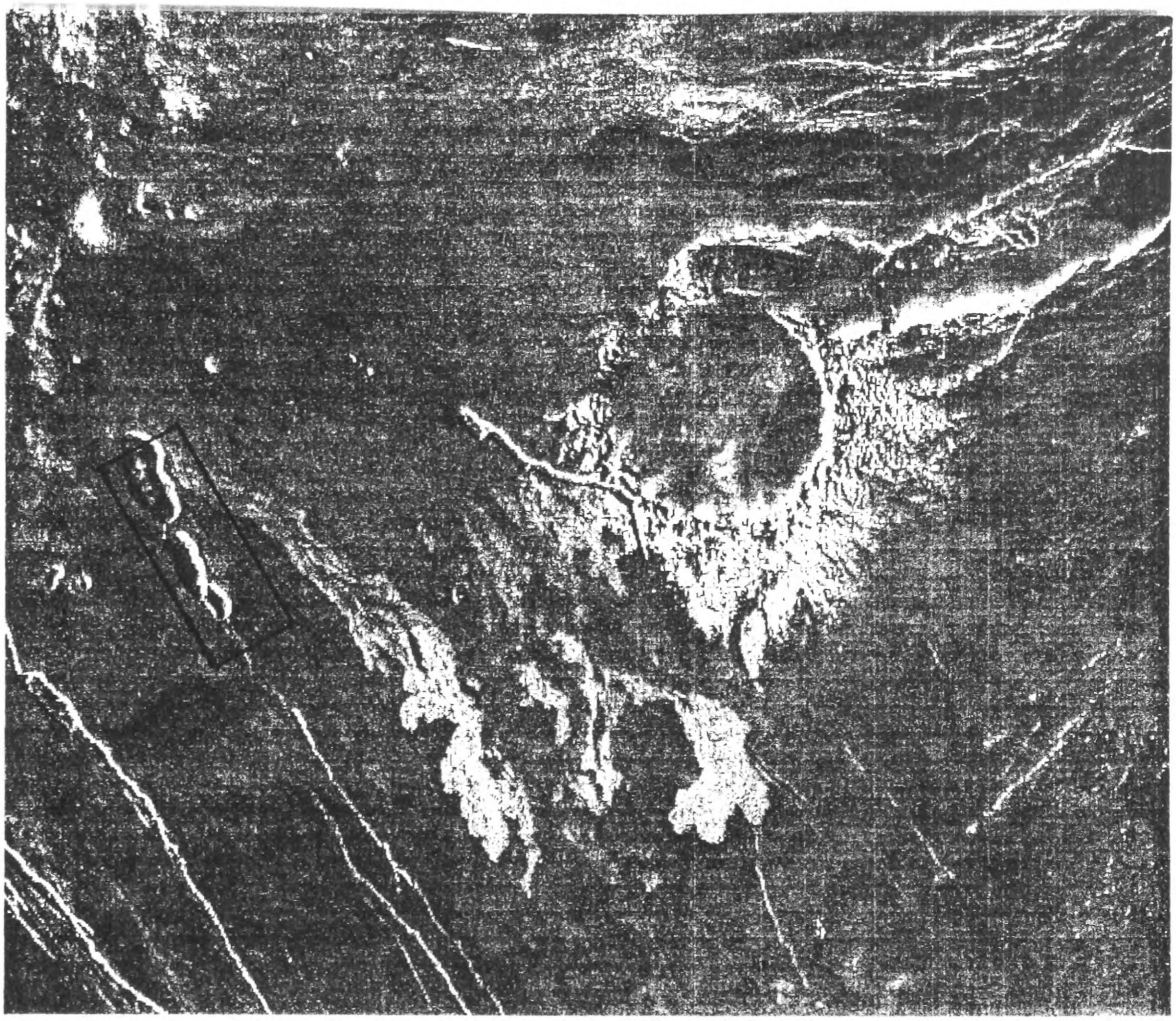


PHOTO 28
Collapsed features and an ancient impact crater.
(F60S352)

20 Kms

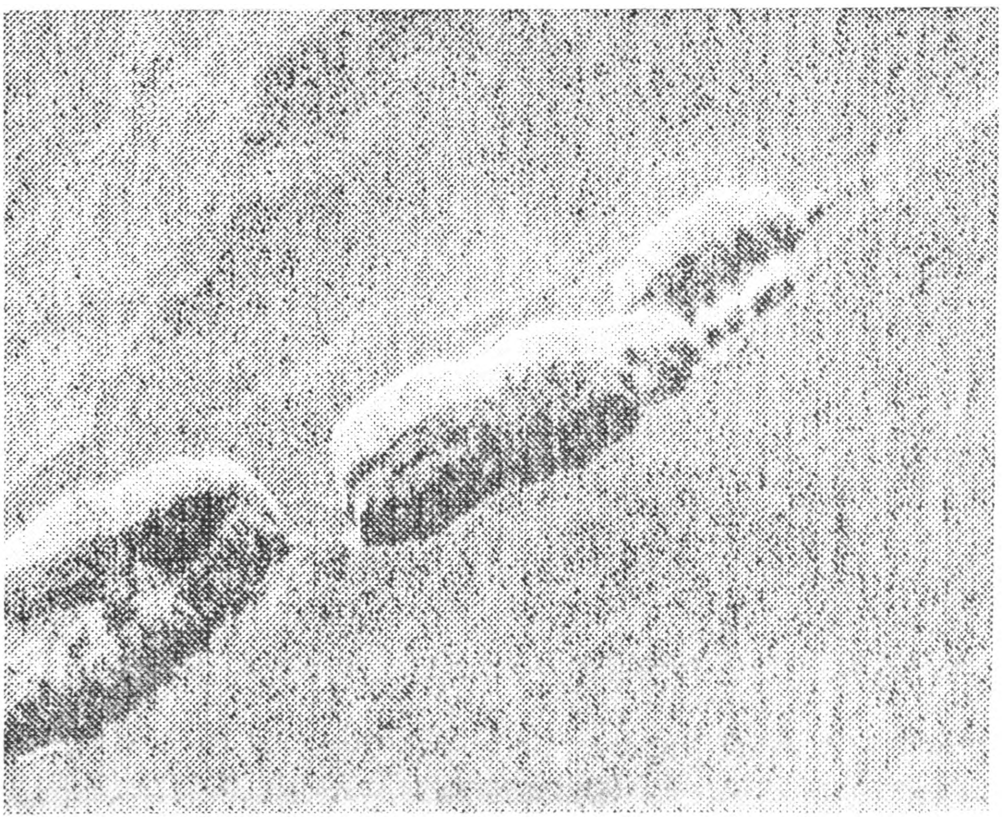
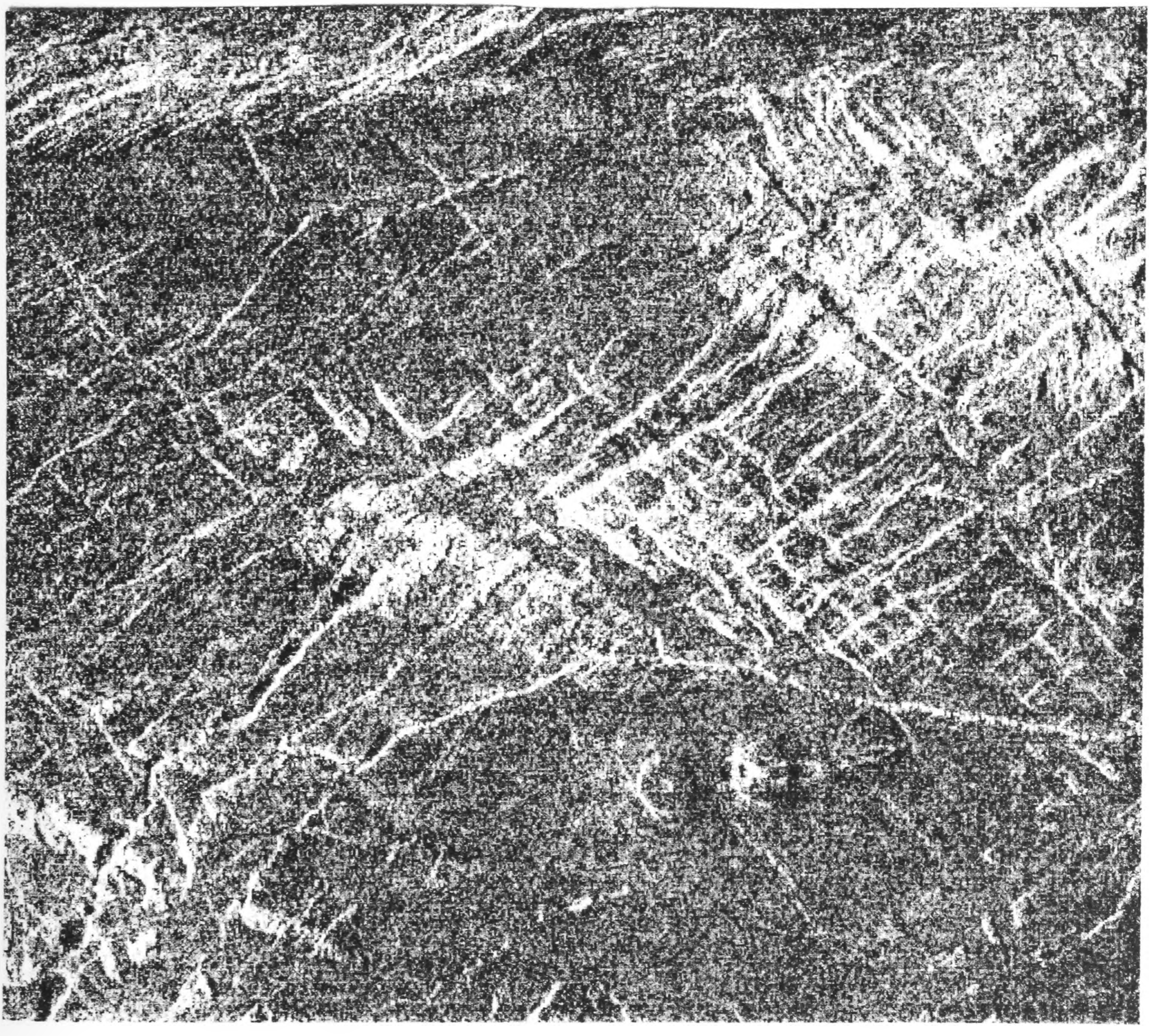


PHOTO 29
An enlarged section of photo 28 showing collapsed magma chambers with associated crater chains.
(F60S355)

PHOTO 30
Pitted craters
and indentations.
(F00N076)



10 kms

Final Analysis of Crater Chains

The vast majority of pictures probably indicate that the collapsed features are not lava tubes but pit craters formed from the movement or withdrawal of subsurface magma. This magma may be at varying depths and a diagram of the structure of Hawaiian pit craters can be seen in Figure 22 on the next page. However, this does not exclude the existence of collapsed lava tubes for the reasons set out below:

1) Some chains run into channels which have carried lava.

2) Some chains vary in size much like one would expect collapsed lava tubes to do.

3) Some chains are seen well away from volcanic areas and do not seem to be associated with fractures or rift zones as pit craters do. These may be due to gravity slips around volcanic intrusions.

4) Conditions favouring the existence of lava tubes such as fluid lava, favourable terrain and large volumes of lava occur on Venus.

Although, some of this evidence is circumstantial, remember Magellan resolution may have excluded the vast majority of collapsed lava tubes. Also, lava tubes only become visible when they happen to collapse.

This matter becomes further complicated when one considers that features in an area are at different ages and therefore, at different eroded stages, even though erosion on Venus is very low compared to the Earth.

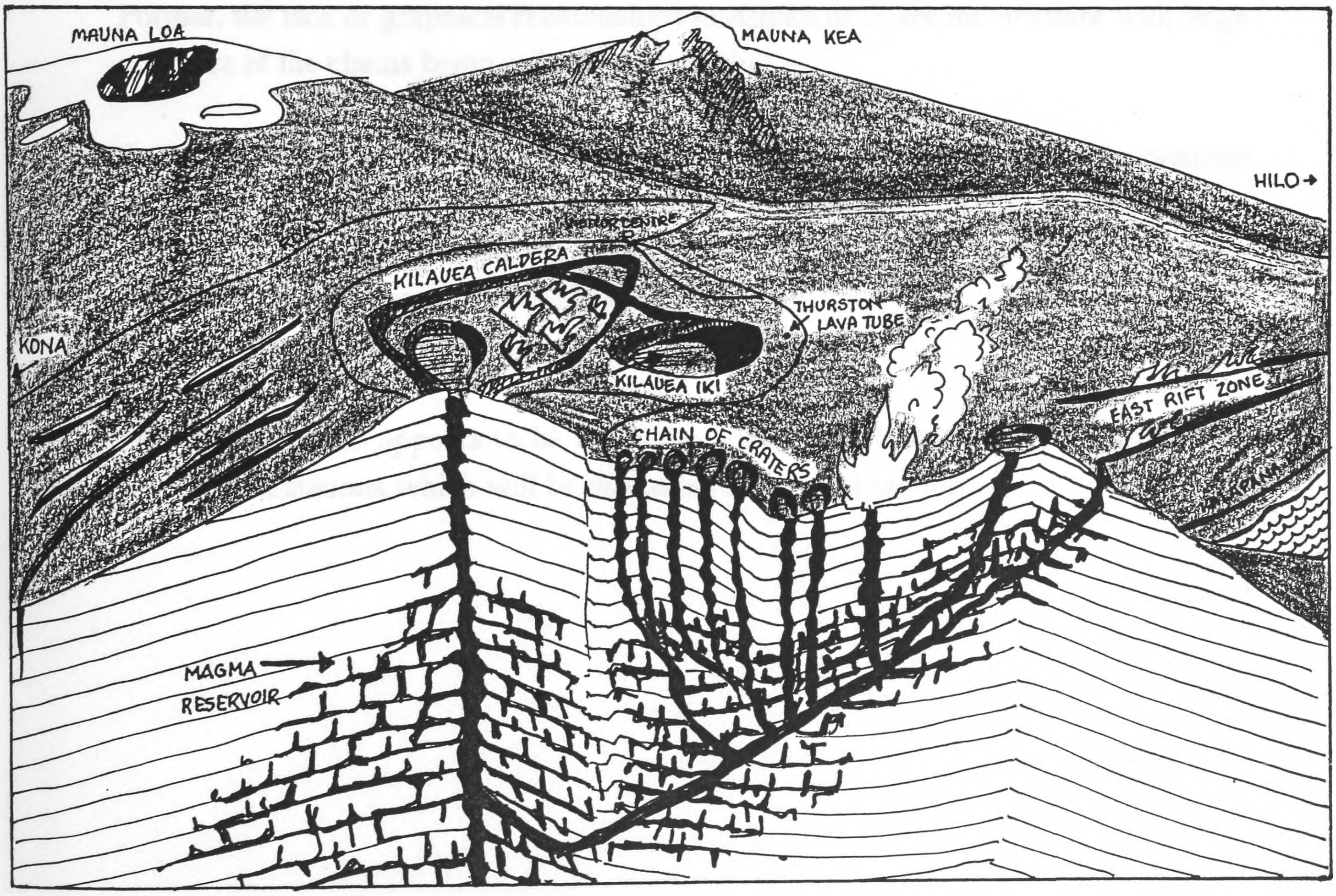
Finally, many of these craters as previously mentioned tended to follow narrow faults and cracks adding evidence to their gravitational collapse.

FIGURE 22B HAWAIIAN PIT CRATERS

A geologic view of the underground plumbing system of the craters reveals a magma reservoir, where molten lava accumulates and intersperses among the rock, creating an area much like a gigantic sponge.

Internal forces of pressure and high temperature build, causing the rocks to deform and the molten magma to rise along the lines of least resistance. The shifting of rock to accommodate the rising liquid results in literally hundreds of earth tremors and an occasional bone-jarring earthquake.

Outbreaks on the surface may take many forms - from a minor steam explosion to a major eruption. They usually can be predicted quite accurately because of the constant study and collection of data being carried on at the Hawaiian Volcano Observatory.



The analysis of the photos enable us to draw the conclusion that most crater chains are in fact collapsed pit craters not lava tubes. Is this, however, supported by the data we obtained in Appendix A?

Yes, it would certainly appear so. Although, crater size is not a good guide to exactly what they are, the crater dimensions found on Venus are more consistent with their terrestial pit crater counterparts. On the Earth we do not find large numbers of aligned pit craters but on Venus we can see as many as 60 aligned pit craters. More importantly, most chains seem to be directly associated with faults or fractures as one would usually expect to be the case with pit craters. Also, the vast majority of crater chains are very straight (224 out 260). This is inconsistent not only with Earth lava channels, Undara's depressions were curved (Figures 8, 9 and 10), but also Venusian lava channels (Photos 10, 11, 12 and 13).

It would be strange to have many sinuous lava channels, yet very few sinuous crater chains which may form collapsed lava tubes out of these channels.

Further, the lack of graphical relationships in Appendix A are inconsistent with large numbers of the chains being collapsed lava tubes.

Crater chains being caused by gas explosions is inconsistent with both observations and the data. Lava looses gas quickly, once it reaches the surface and although it could cause a couple of craters, certainly not the number that are present on the Venusian surface, many of which are found well away from the magma surface entry point.

Finally, there also appears to be a definite relationship between these crater chains and the indentations which will be discussed in the next section.

Summary

A large number of crater chains are found on the Venusian suface. These chains average about 25 km in length, though some are over 200 km. Their width is around 500 m but chains with diameters of over 1 km are not uncommon.

An analysis using collected data and photos provides overwhelming evidence that these chains are not only collapses but in the vast majority of cases are collapses associated with pit craters. These pit craters form as a result of the withdrawal of magma in subsurface cavities. Collapsed lava tubes may well be present either hidden among the much greater number of pit craters or below the Magellan radar resolution.

There is little evidence for crater chains having an explosive gas venting origin.

Later we will see Martian crater chains in Valles Marineris where it is questionable as to whether they are of volcanic origin.

3.2.3 TYPE C - INDENTATIONS

These may be best described as depressions (Photo 31) that are normally closed at both ends. Their shape is usually long and narrow but shorter oval-like ones are quite common.

In the region of Venus studied, particulars on 200 indentations were recorded and these data can be found in Appendix B (Table 1). Indentation length ranged from a huge 307 km down to a small 1.3 km, though the average was only about 20 km. Their width was anything from 0.4 km to around 12 km but the average was 3.1 km.

Results

Appendix B (Table 1) also shows other details which were recorded besides the basic number statistics. These include:

1) the shape of the indentations, these fell into 3 broad classes - oval; round; or elongated.

2) whether indentations overlaid faults or fractures. If no faults or fractures were seen than a 'dash' was recorded.

3) whether the faults or fractures overlaid the indentation, (again if they were present).

4) the indentation's angle to the fault or fracture if they existed.

5) whether the indentations had visible shadows.

6) a guide to the age[3] of an indentation by classifying them as old \ medium \ or young.

---

3 *The technique used here was similar to that used to date craters. That is, the state of degradation, pristine (young) to well-worn (old), was examined.*

The following points become evident from a study of the table in Appendix B (Table 1).

* Like the crater chains there is considerable variation in both length and width of the indentations.

* That most indentations are elongated in shape (139 out of 200 or approximately 70%).

* Where indentations were found most existed in images with faults or fractures (120 out of 200) and roughly a third (36 out of 120) laid on top of these faults or fractures.

* Barely any faults or fractures (1 out of 33) laid on top of indentations.

* The vast majority of Faults or fractures intercepted the indentation at 0 degrees, that is, were parallel (49 out of 57) to the indentation. The rest met the indentation at 90 degrees, that is, were perpendicular to it.

* Only a relatively small number of indentations had shadows (57 out of 200).

* Most indentations were medium in age (122 out of 200) but there were a number of old ones (32) and young ones (46).

<u>Graphical Relationship</u> (see Appendix B)

Table 2 and its accompaning graph *Chart 2* shows the number of indentations in a particular length class. This indicates that most indentations are in the lower end of the range in regard to length. This is followed by a rapid decrease then a gradual tapering off. Interestingly, the number of indentations of length between 40 and 100 km remains relatively constant. However, because we are dealing with such small numbers in this range no conclusions can be drawn.

Table 3 and its corresponding graph *Chart 3* show the perferred range of indentation widths is quite large. The marked increase from below 1 km up to about 2 km is quite noticeable but may be explained by the difficulty of manually detecting such indentations. Again, the usual tail is evident. It is important to note that most indentations, especially the elongated ones, varied in their width, some considerably, so the recorded width is an average value.

Chart 1 shows the result when all of the indentations in *Table 1* are placed in order according to their length and then plotted against their corresponding widths. Again, like the crater chains the random pattern indicates ***no*** relationship exists between average indentation length and their width.

Photos of Indentations

Before we make an analysis of the data and draw any conclusions let us first have a look at some photos of some different types of indentations.

The photos are by no means representative in number of the different types of indentations but merely give an idea of the many forms an indentation can take. The more unusual ones take some explaining in regard to their exact origin but I feel most can be explained as having formed in a similar way.

Also, some indentations are quite similar to lava channels and as such the distinction between them is not always clear.

PHOTO 31 - F60N334 shows a good cross-section of a number of indentations. A small highly elongated one is seen towards the upper centre, as well as a well-defined oval shaped indentation just left of centre. The long unusual indentations in this picture, towards the left, are a series of lava channels or maybe even lava tubes arranged in a complex manner. This is evidenced by some pitted craters running parallel to many of the indentations and possible flow patterns within the indentation. Any features that once existed in the righthand section of the image appear to have been obliterated by lava flows.

This image is located near the co-ordinates 60N334 in the region of Vesta Rupes.

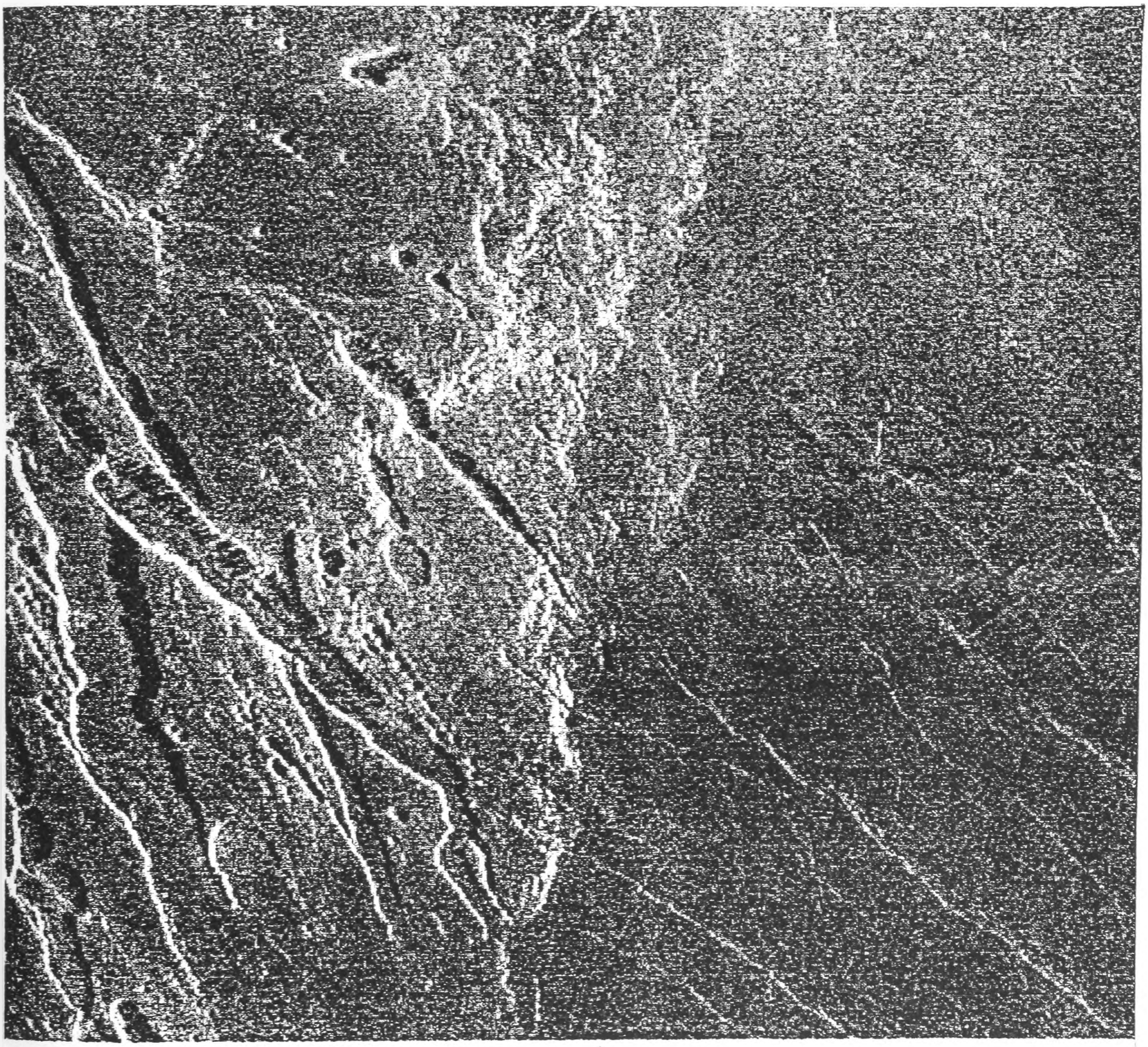
PHOTO 32 - F05S076 is quite a remarkable picture and very valuable in helping explain the origin of these indentations. What we have is an elongated indentation, with the hint of a shadow, that is about 3 km wide and 15 km long. On the upper end is a well-defined circular crater having a diameter of about 1 km. This crater certainly appears to be a drainage crater and one supposes that the indentation was once a lava pond whose lava level dropped as a result of this drainage crater. The similarity between the floor of the indentation and the section on the left backs up this evaluation as well as the smoothness of the indentation floor.

This image is located in western Aphrodite at 05S076.

PHOTO 33 - F10S087 contains a number of features and shows how diversified the surface of Venus can be. It appears as a young area, as evidenced by many of the sharp features and is situated on the flanks of a volcanic system. An elongated section running across the image at the top appears as an excavation or wide canyon with a crater at each end. It may be a surface tear due to tensional forces or alternatively, but less likely, magma may have poured out of the left crater ran a course across to the right and exited down below the surface through this right crater, or it may have simply ponded. It also overlies two depressions yet hasn't flowed into them which probably means it is lower than these depressions. A number of crater chains are also visible as well as some pitted areas. Some more excavations can be seen in the lower left of the image. Altimetry data dictate the flow of lava in these cases, as being upwards and the course dwindles away much like a terrestial watercourse. Baker et al., 1992 has catagorised this excavation as being a sinuous rille.

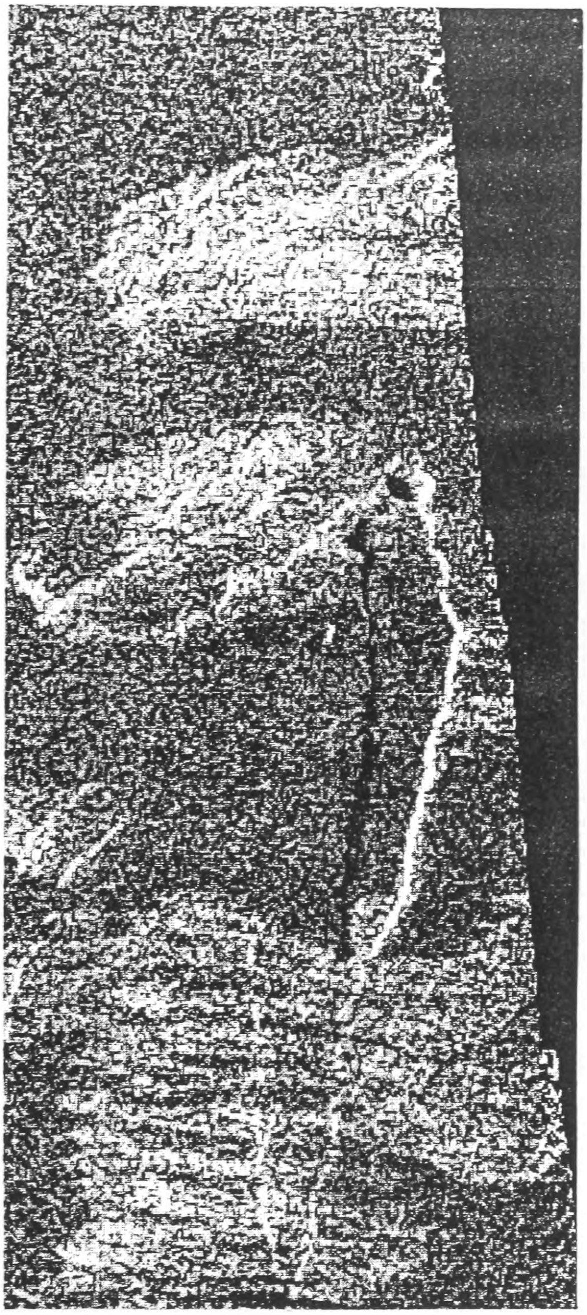
This image can be found near the previous image at 10S087.

PHOTO 31
A number of indentations of various shapes and sizes.
(F60N334)



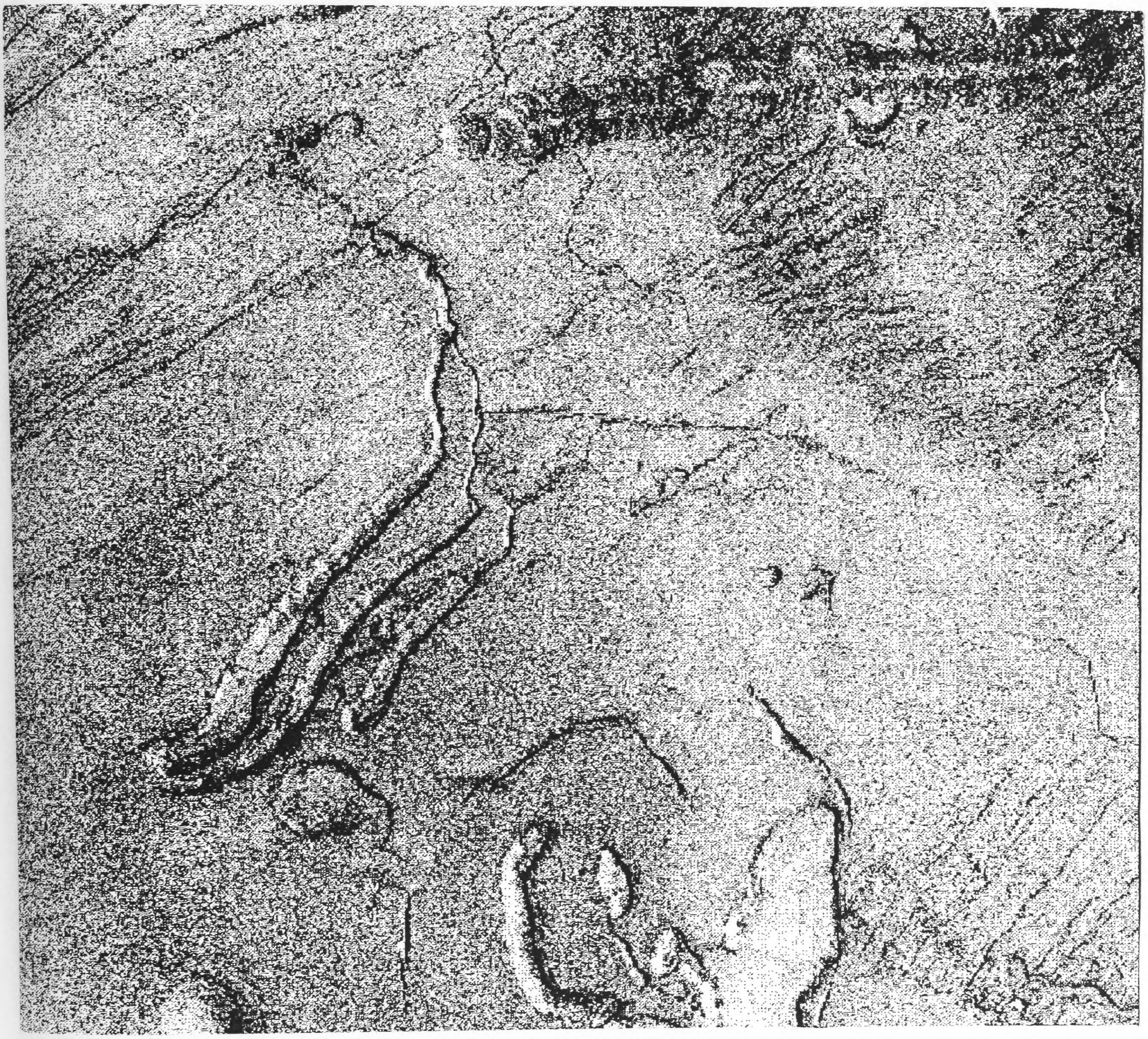
5 Km

PHOTO 32
A drained indentation.
(F05S076)



10 Km

PHOTO 33
Diversification
of the Venusian
surface.
(F10S087)



20 Km

PHOTO 34 - F30S357 is an image of a corona and shows a number of channel-like indentations surrounding a central lava pit-region. These indentations are tube-like in appearance and crisscross each other in a manner suggesting this volcanic region was once quite active. A very large tube-shaped indentation, over 60 km long, can be seen in the central dark zone at the lower right of the picture. This dark zone is a plateau (see profile below the photo) and contains an upraised rim having quite smooth lava which seems to have remained well confined. Note, the presence of some crater chains, towards the top of the picture, leading into the tubes. These are probably pitted craters rather than collapsed lava tubes. The region also appears to contain a number of graben.

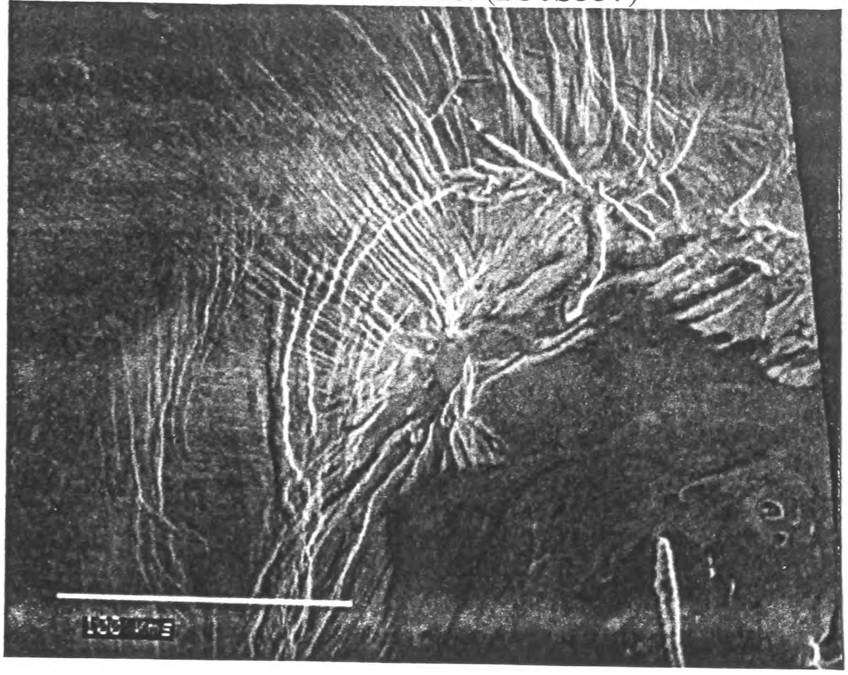
This picture can be located near Eve in the vicinity of Alpha Regio at co-ordinates 30S357.

PHOTO 35 - F10S087 again contains a number of indentations heading in more or less the same direction. What makes this image unusual, however, is the fuzzy-like indentation features. This would seem to indicate that this region is older than some of the others since the features are less defined. A crater chain is also visible at the bottom of the image. This image is located in the central highland areas of Aphrodite Terra at 10S087.

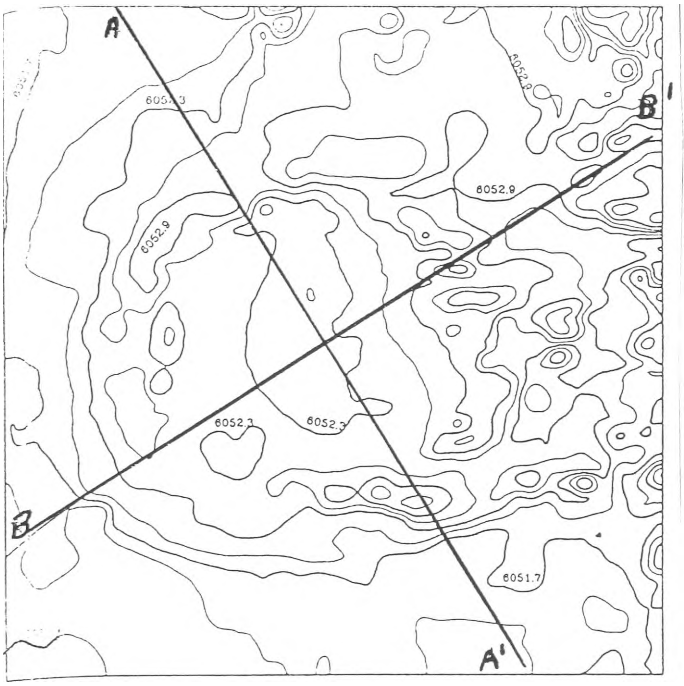
PHOTO 36 - F30S351 is a good image of a lava pond, which is shaped like a tadpole, and has a still attached channel. Whether the lava flowed upwards to form the pond or is/has drained partially downwards is indeterminate. The word "partially" is used because the pond appears to be slightly concave, indicating that the lava level has dropped somewhat. Note also the bright edge on both the pond and the attached flow channel which indicates the presence of flood levee banks.

The image may be located near 30S351 which is to the west of Alpha Regio.

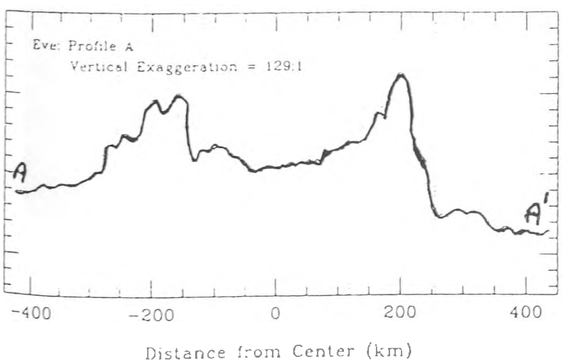
PHOTO 34 Channel-like indentations. **(F30S357)**



Topographic contour map of Eve. Contour interval is 300m.
A-A', and B-B' show the locations of the other two profiles presented (Janes et al, 1992)



Altimetric profile A-A' across Eve



Altimetric profile B-B' across Eve

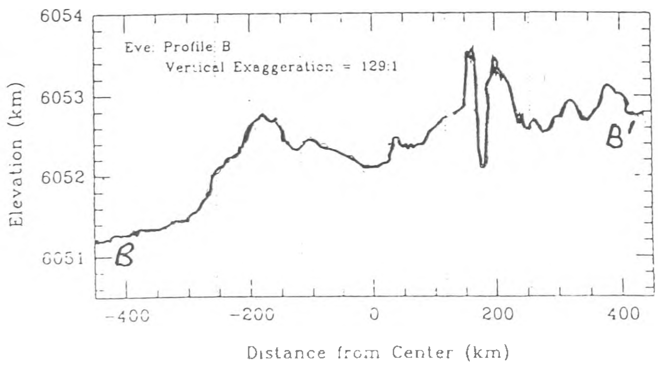


PHOTO 35
Old indentations.
(F10S087)

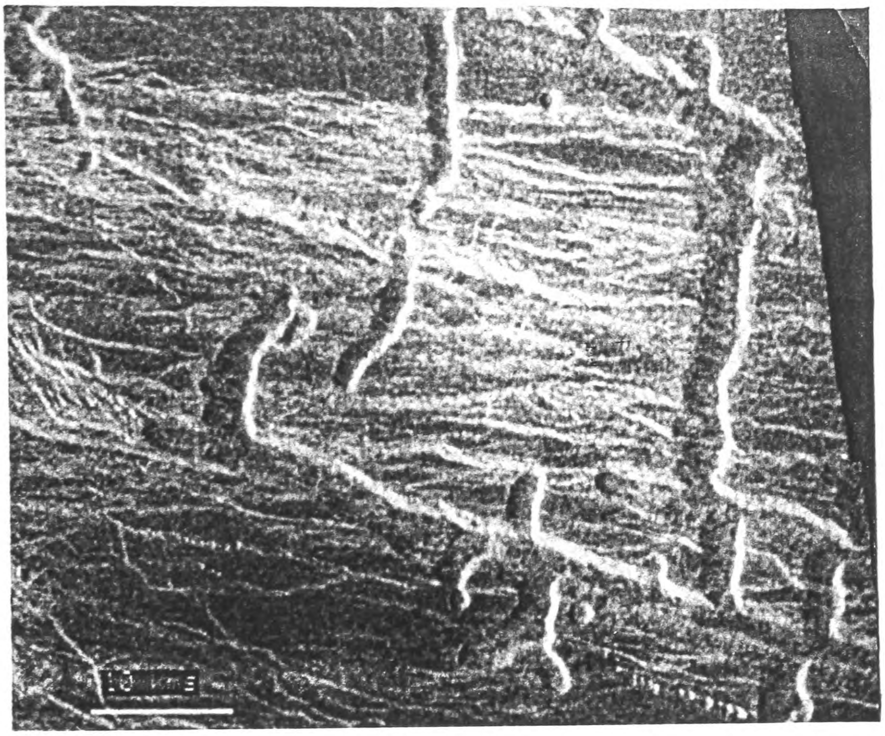
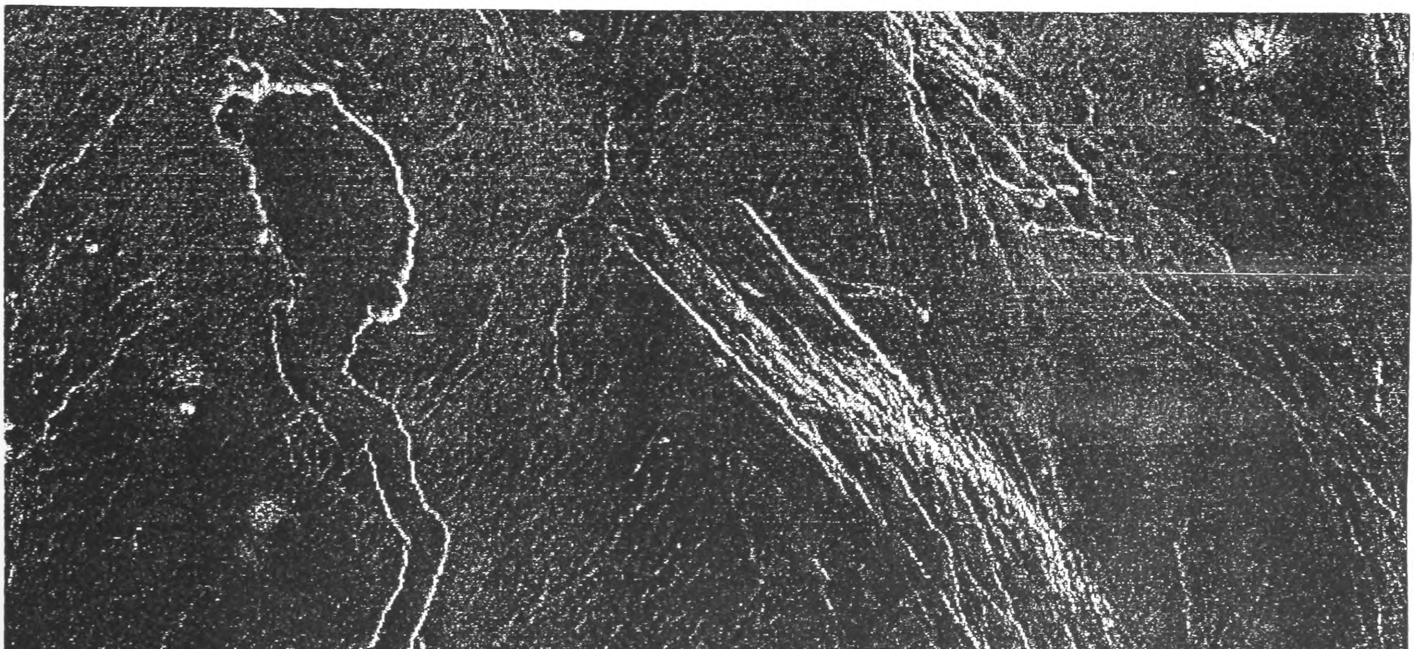


PHOTO 36 Lava ponding. **(F30S351)**



10 Km

PHOTO 37 - F30N123 on the next page appears as a quite strange lava flow. There seems to be a raised cylindrical ropy section extending from the bottom left hand corner of the picture up to the centre. This raised section then curves around to the right appearing to open up much like the mouth of a terrestial river. Is this the Venusian equivalent of the inverted lava tube we saw at Undara called 'The Wall'. The one in the image is at least 70 km long and 2 or 3 km wide.

The image is located at 30N123 in the plains of Niobe Planitia.

PHOTO 38 - F30S351 indicates that Venus probably also has very viscous lava flows. These are a series of dome-like hills averaging 25 km across and 750 m in height that sit on the eastern edge of the Alpha Regio highlands at 30S351. They are considered to be eruptions of viscous lava from vents in ground so level that the lava simply flowed evenly in all directions, like thick pancake batter poured on a hot grill, hence their name, pancakes (Head et al., 1992). Their sides are very steep and they are considered to be several hundred metres high. 145 have been found to date and these domes display surface morphologies similar to extrusive domes of rhyolitic and dacitic composition on the Earth (Head et al., 1992), but the Venusian domes are much larger.

PHOTO 39

When all of the Magellan images are combined, an overall view is obtained. This view looks down on the north pole, which is at the centre of the image. It gives a better view of Maxwell Montes, the bright object just below centre. Many other features are also present.

PHOTO 37
Possible Venusian equivalent of "The Wall".
(F30N123)

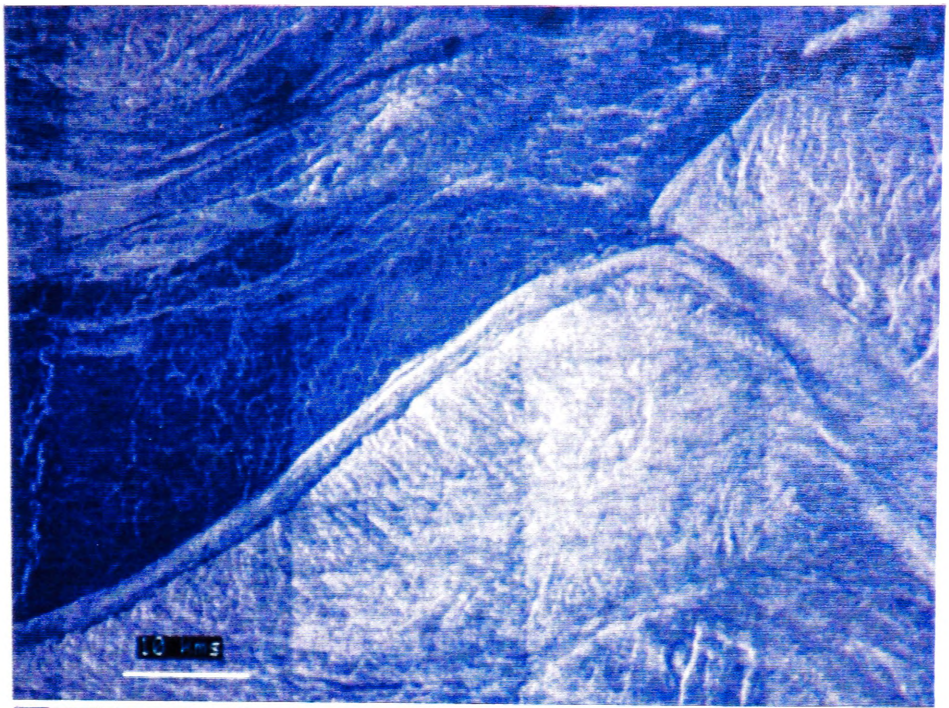


PHOTO 38
The Pancakes.
(F30S351)

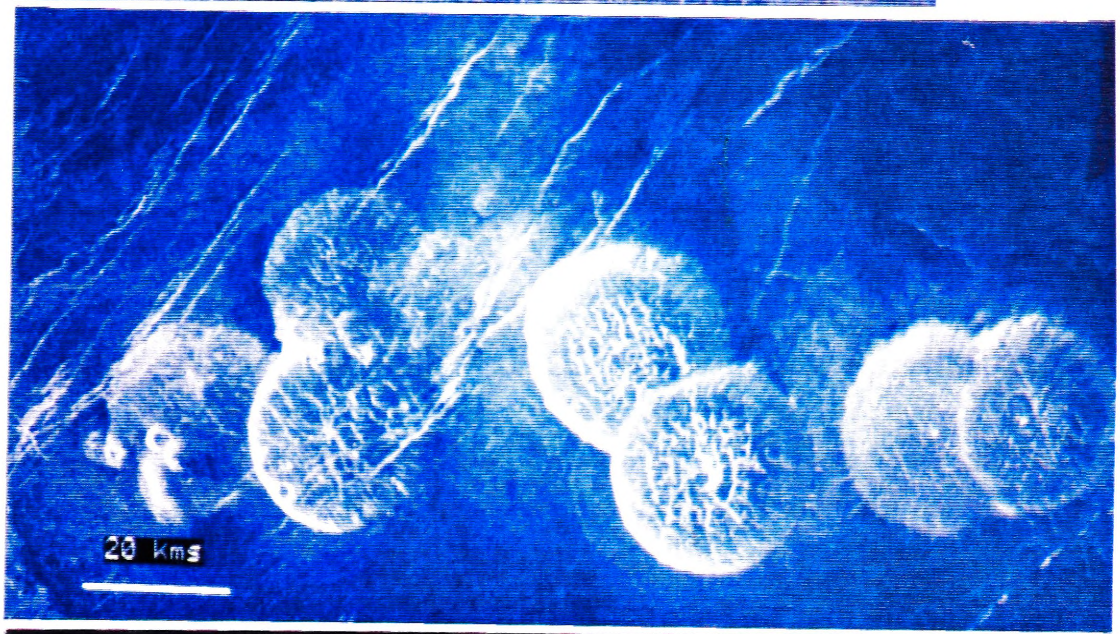
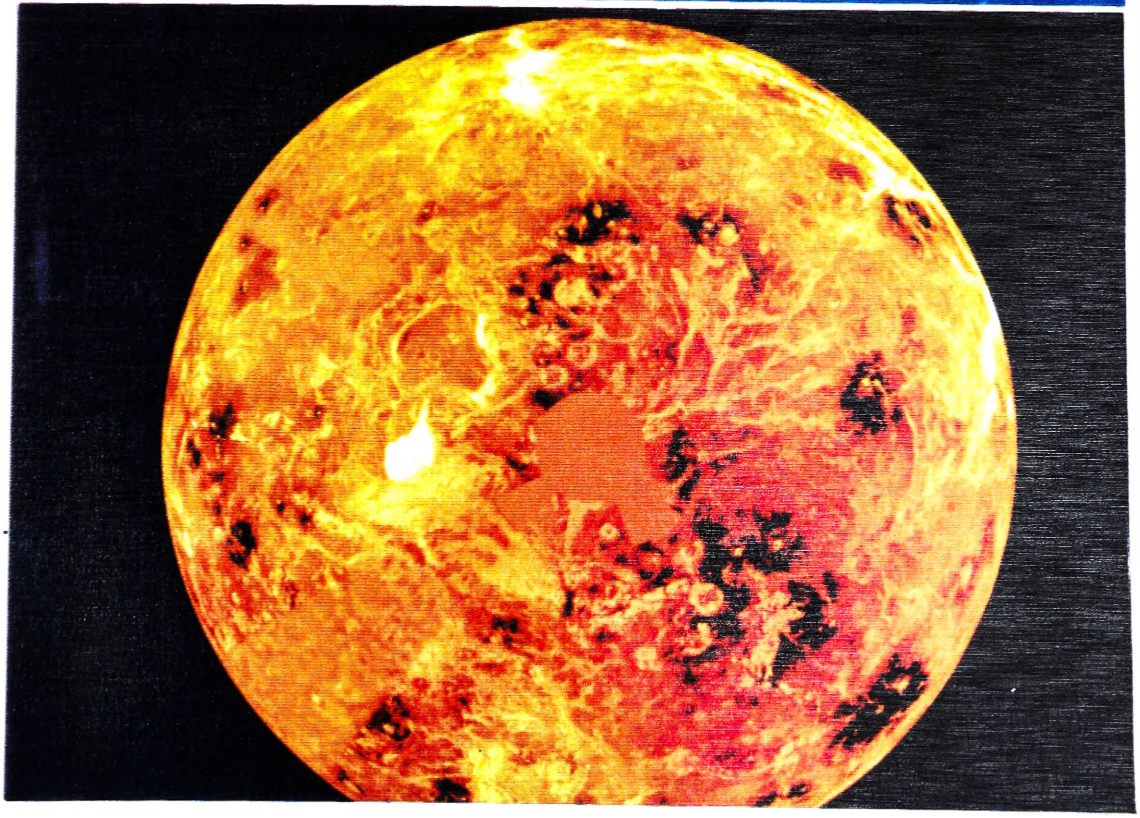


PHOTO 39
Venus -'Unveiled'.



Final Analysis of Indentations

Let us begin our analysis by first summarising what we have found out so far on depressions.

Indentations or depressions are mostly elongated in shape, can have considerable length (over 300 km) but are usually somewhere between 5 and 30 km, and have an average width of about 3 km. They usually ran along fractures which ran parallel to other fractures in the vast majority of cases. Only some indentations had shadows so a large number may be relatively shallow in depth.

The indentation statistics are quite similar to that of the crater chains, although indentations are wider, and often run into one another, so one might expect them to have a similar cause.

Volcanic depressions in general can be divided into those formed by explosion and those formed by collapse or down faulting. At Undara the depressions were interpreted as being formed as a result of lava ponding. Many of the depressions on Venus, likewise, seem to be able to be interpreted this way as well. Although, the wide depressions at Undara were much smaller, 50 - 100 m wide, theoretically, lava ponding can be any size if conditions are right. Near Exford, Victoria there are two large depressions that are about 1 km wide and 50 m deep (MacDonald, 1972).

We saw that once formed, these ponds tend to perpetuate themselves during the life of the flow and later drain themselves, resulting in a collapse. An interesting point is that, again at Undara, these ponds were connected to many of the lava tubes, see the earlier Figure 13. So what we see on Venus is lava draining from beneath the crust of an extensive lava sheet forming large closed depressions or indentations. This can also explain why the floor of many of these depressions appears smooth. As well, there are other similarities between Venusian indentations and Undara's wide depressions. These include similarity in shape, proximity to volcanic activity and lava channels, and the fact they tend to become elongated in the direction of the lava flow.

In addition, many indentations can simply be explained as graben, although their pattern and origin may be far from simple.

There seems to be four possibilities here, three of which may give a smooth depression floor:

1) The lava pond does not completely empty, thus leaving a smooth layer of lava (that is, no collapse), **or**

2) The roof of the lava pond slowly drops as one unit, thus maintaining its integrity, giving a smooth appearance, **or**

3) The roof of the lava pond collapses completely causing rubble but this rubble may be covered later by lava flows, again giving a smooth appearance, **or**

4) The lava pond roof again collapses entirely, but remains as rubble on the floor of the depression, thus giving a rough appearance.

Some of the indentations certainly have a floor which is not smooth and show evidence of lava having moved through them. This may well have occurred at some time after they had formed. As well, since indentations are often found along fractures, one can easily envisage lava seeping up through these fractures ponding and later collapsing. Or, large magma chambers close to the surface collapsing once their magma has withdrawn.

<u>NB</u> Some indentations, however, appear by themselves away from visible lava and may be harder to explain.

Magma Chambers

There has been much mentioned recently in this study about magma chambers and the possibility of them explaining many Venusian features. Although, the exact source of magma on Venus as well as their connection with their magma chambers is entirely speculative and beyond the scope of this thesis, one possible scenario is briefly outlined below.

As solid material rises from deep below, it undergoes a tremendous decrease in pressure. This reduction in pressure allows some previously solid minerals to melt. The lighter, melted fraction of the rock moves upward, because of its lower density, separating from the solid residue as it rises.

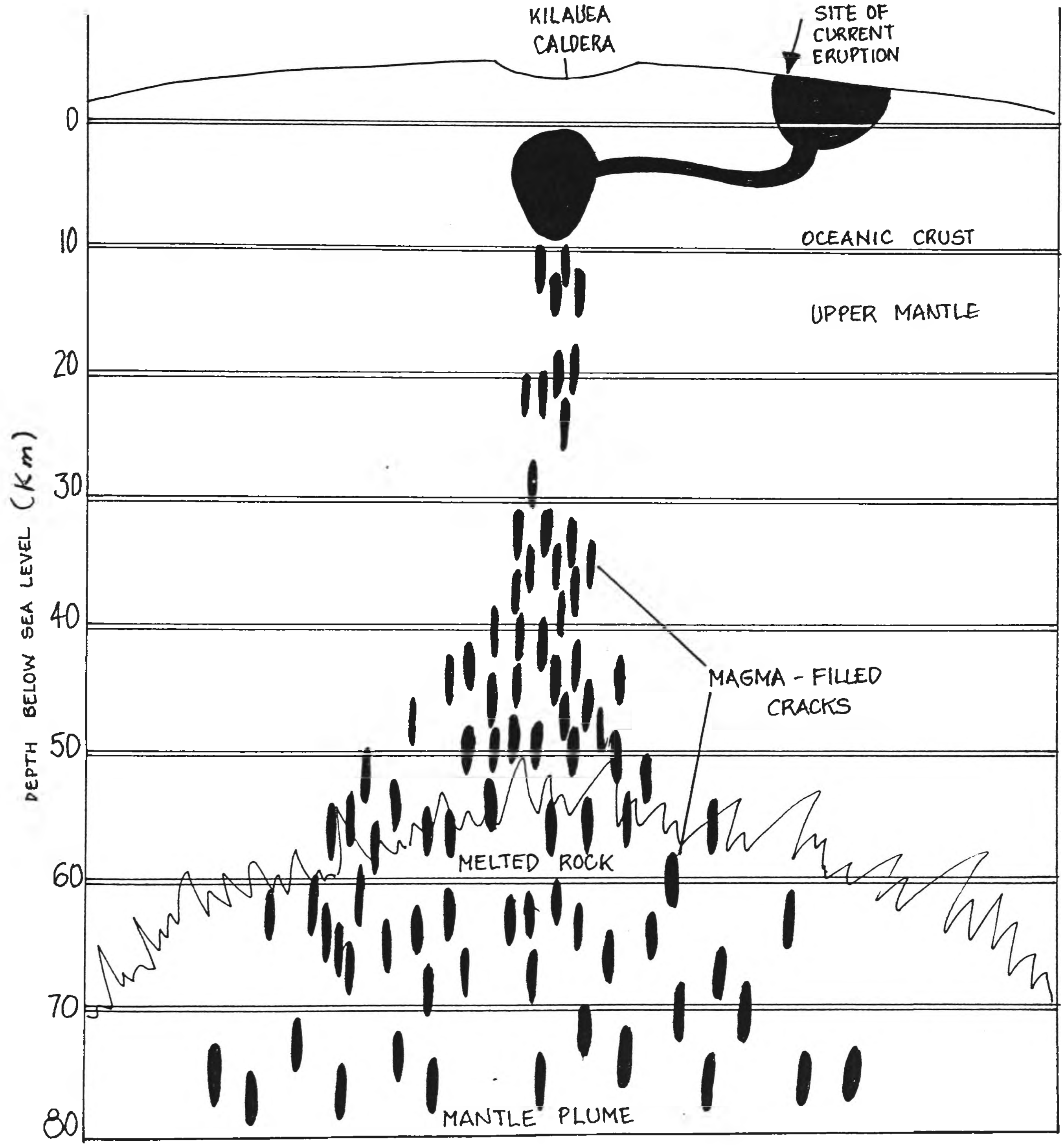
Laboratory experiments (Dvorak et. al., 1992) indicate that the rising magma collects in pockets. These pockets of liquid rock force their way through solid rock by creating and flowing through lens - shaped cracks.

Now, on Venus a good deal of this magma may accumulate in shallow magma chambers or seep through the vast numbers of fractures or faults, revealed by Magellan, apparently caused by uplift and subsidence due to magma pooling then draining beneath the surface. See Figure 23 on the next page. A comparison between the Earth and Venus is illustrated in Figure 24.

It may seem odd that after its long journey upwards, rising magma would pause to accumulate in shallow chambers so close to the surface. This behaviour, however, is thought to be attributed to the slight difference in density between the rising magma and the rock that may form the uppermost part of a volcano.

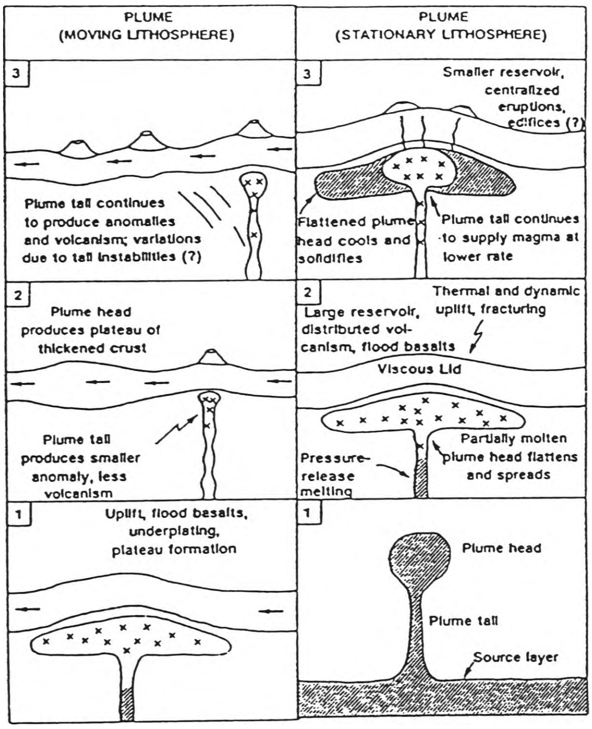
FIGURE 23 HOW VENUSIAN LAVA MAY ACCUMULATE

Rising buoyant columns of hot material (magma) forces its way through the surrounding rock. The magma then collects in a reservoir some unknown distance below the surface. The molten rock may erupt upwards, flow through horizontal conduits to emerge some distance away, or simply seep through the numerous fractures or faults.



<u>FIGURE 24</u> A COMPARISON BETWEEN VENUS AND THE EARTH

The nature and consequences of hot spot/mantle plume development on Venus and on the Earth (Head et al.,1992).



Summary of Indentations

A large number of indentations or depressions are visible on the Venusian surface. Although, the most obvious features are long and narrow, shorter oval ones are not uncommon.

Their lengths range from 2 km to over 300 km. Their widths are typically 2 km, although, a few exceed 10 km. Some are deep, as evidenced by radar shadowing, but most are quite shallow. Sharp edges indicate some might be quite young and have suffered little gravitational slumping.

Many appear to have been flooded with lava after their formation. Many indentations also, seem to be associated with fractures as do crater chains. A good many of their origins seem to be connected with lava pooling and appear similar to the wide depressions at Undara.

A considerable number of indentations are also graben.

Some, however, which do not appear as graben, are not associated with any visible volcanic activity.

CHAPTER 4 LUNAR LAVA TUBES AND CHANNELS

4.1 *Introduction*

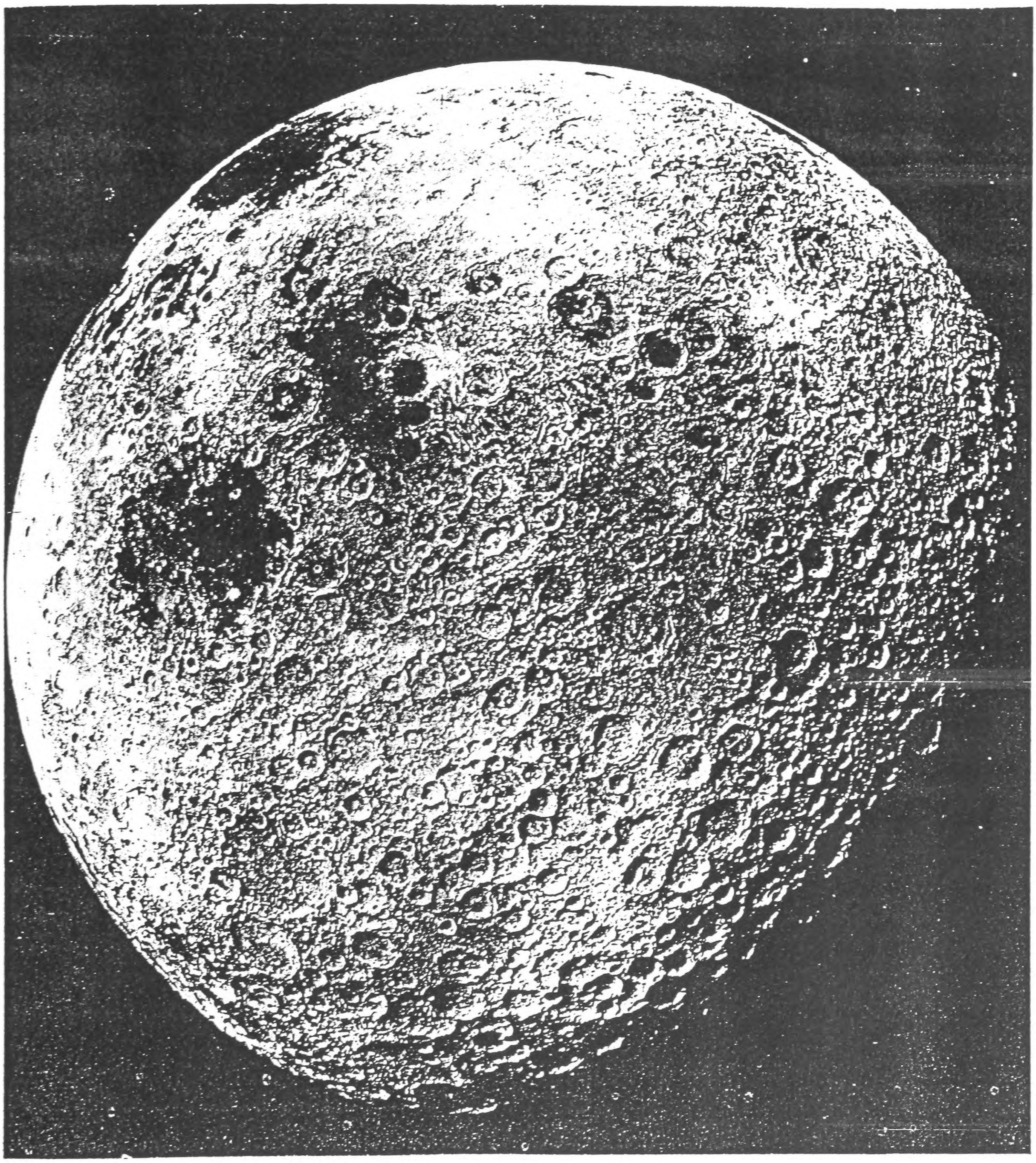
Space probes have revealed that volcanic activity has occurred at least sometime in the past on both the Moon and Mars.

In regard to the Moon, it is now well established that volcanism has played a major role in the formation of the Moon's surface with the dark mare regions (Figure 25) having resulted from the flooding of low-lying areas by lava. Other areas have revealed dome-shaped, possibly shield volcanoes, 10 km or more in extent and many numerous craters have been demonstrated to have resulted from volcanic activity (Fielder et al., 1971).

A number of important similaries relevant here between Mars, Venus and the Moon include no evidence of plate tectonics and the appearance of channel-like features. These will now be looked at more closely.

FIGURE 25 THE MOON

The moon is dominated by rugged regions covered by craters mostly formed during intense meteorite bombardment about 4.5 to 3.5 billion years ago. In the upper left are dark, smooth lava plains called maria, formed about 3.5 billion years ago. (NASA, Apollo 16).



4.2 *Lunar Rilles*

Fissures or channels in the lunar surface are referred to as rilles or rima.

Three types are recognised (Allaby, 1991 and others) :

a) **Straight rilles** - these are typically 1 - 5 km wide and hundreds of kms long (Figure 26).

b) **Curved or arcuate rilles** - these are variants of straight rilles, with similar dimensions (Figure 27).

c) **Sinuous and meandering rilles** - these have a snake-like or wandering appearance of varying size (Figure 28).

These rilles are present in large numbers, varying in form and dimensions. Some are U-shaped, others V-shaped in cross-section. Some have a very mildly curving or serpentine course (at times quite accentuated and mature) which can be compared to slow-flowing terrestial water courses.

The vast majority of these rilles are continuous along their entire length and have parallel or sub-parallel rims. Others take the form of elongated depressions or pseudo-craters. Several of the major rilles have a terraced floor. The dimensions of these rilles varies considerably as well, being from tens to hundreds of km long and from several hundred to several km wide. For example, the meandering rille which runs along the floor of *Vallis Alpina* is about 300 km long, and the *Vallis Schroteri* reaches a width of 9 km.

Some of these rilles originate from craters; others show no evidence of any particular origin. The origin is usually at a higher altitude than the rest of the rille and often the width and depth of the rille tend to decrease toward the end opposite its origin. Less frequently, these dimensions decrease at both extremities. In the majority of cases, the rille seem to gradually disappear. Occasionally they present evidence of the deposition of material.

In some very rare cases, the sinuous rilles seem to have tributaries or they are anastomosed. Some rilles display a certain "rejuvenation" becoming unexpectedly deeper and wider. Others open up toward the "tail" and their depth decreases. Most of the sinuous rilles avoid the ridges and clearly tend to deviate from the highlands. According to one study by J.B.Murray (Fielder, 1971), approximately 37% of the sinuous rilles do not have craters at the head, probably because some of these rilles were covered by lava flows. Some sinuous rilles, such as *Hadley Rille*, are on the crests of topographic highs (Greeley, 1971).

According to some observers, the sinuous rilles are associated with mare-type material and are generally absent in the highlands.

Some of these rilles are undoubtedly very old. For example, an excellent Apollo 15 photo (Figure 29) shows the *Hadley Rille* is deformed by two small craters whose morphology attests to their having undergone a lengthy process of degradation.

FIGURE 26 STRAIGHT RILLES

A) The forked rille Hyginus in Mare Vaporum with its associated craters. (NASA, Lunar Orbiter).

B) Linear Rilles (lunar graben) striking through the 60 km diameter crater Gocienius (Apollo 8, NASA).

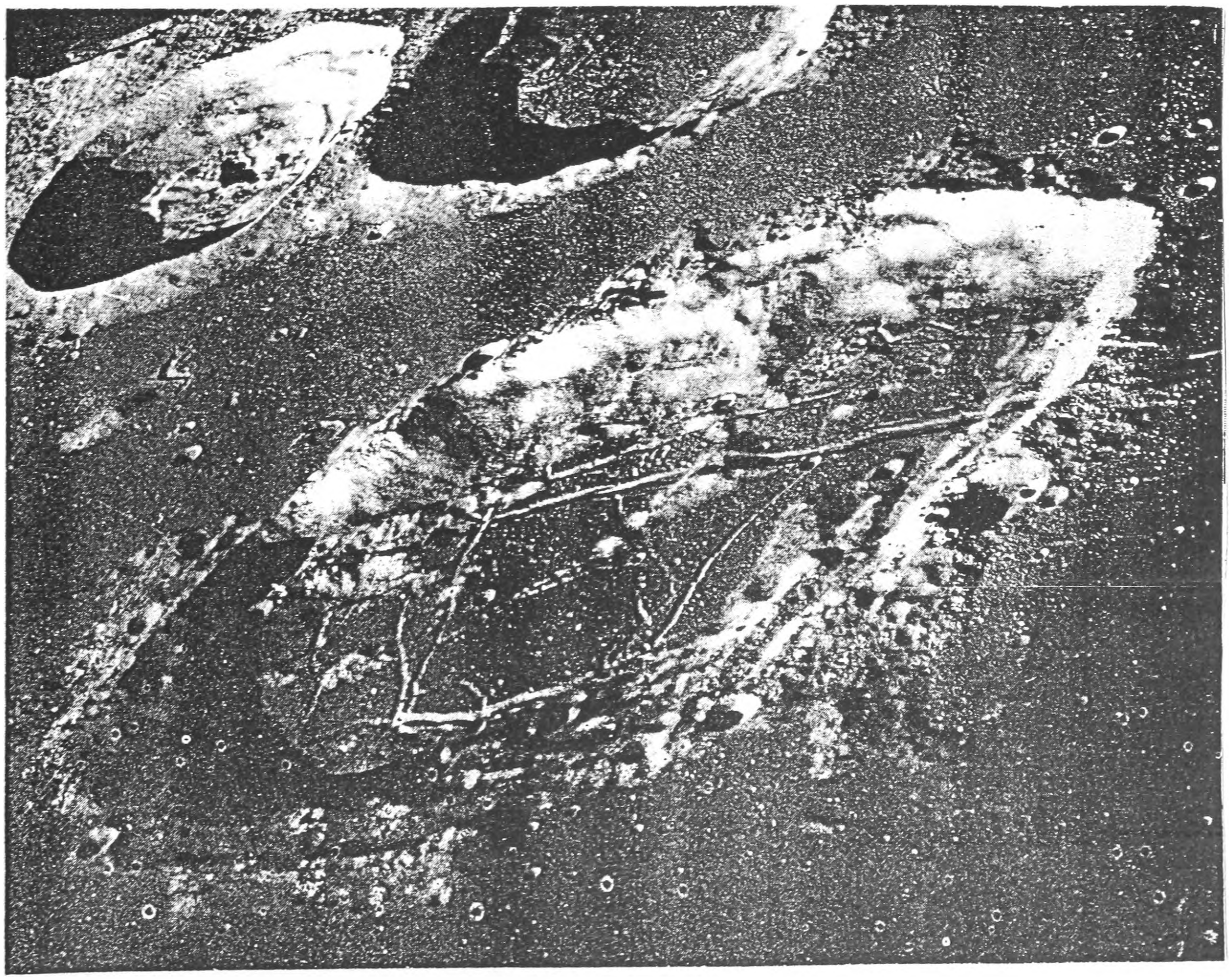


FIGURE 27 CURVED OR ARCUATE RILLES

Arcuate rilles (graben) surrounding the east side of Mare Humorum. North is at the bottom. (NASA, Lunar Orbiter IV).

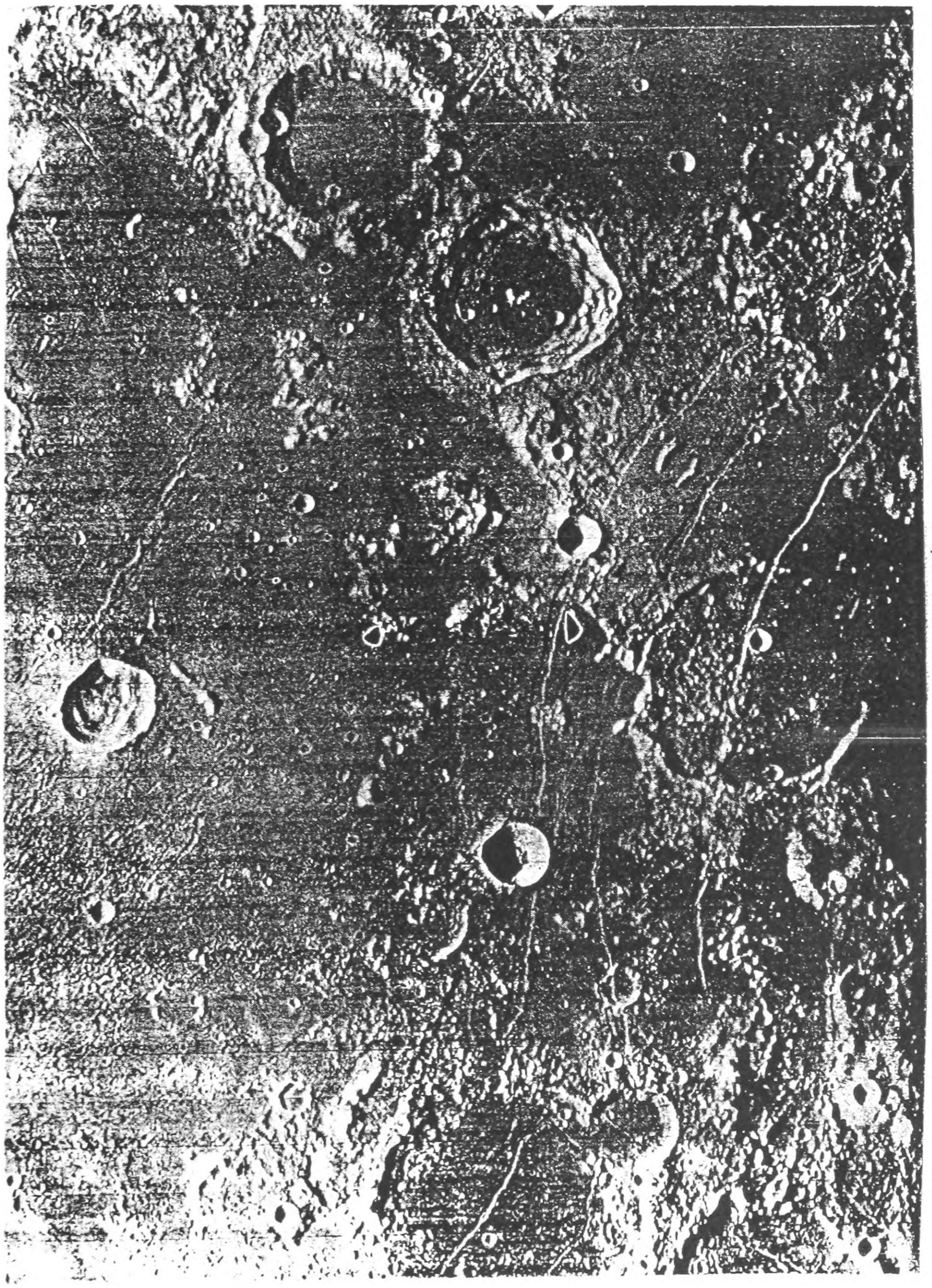


FIGURE 28 SINUOUS RILLES

A group of sinuous rilles NE of Aristarchus. The large crater, half of which is visible at the bottom of the picture, is Prinz. The rilles to the north of Prinz illustrate several characteristics of sinuous rilles. Like on Venus (Photo 33), many begin in a crater or depression and become shallower in what appears to be a downslope direction. Most have flat floors. Some sections of the rille are quite straight, implying some structural control. One rille cuts through a highland mass in the centre of the area. Framelet width is 4.5 km. (NASA).

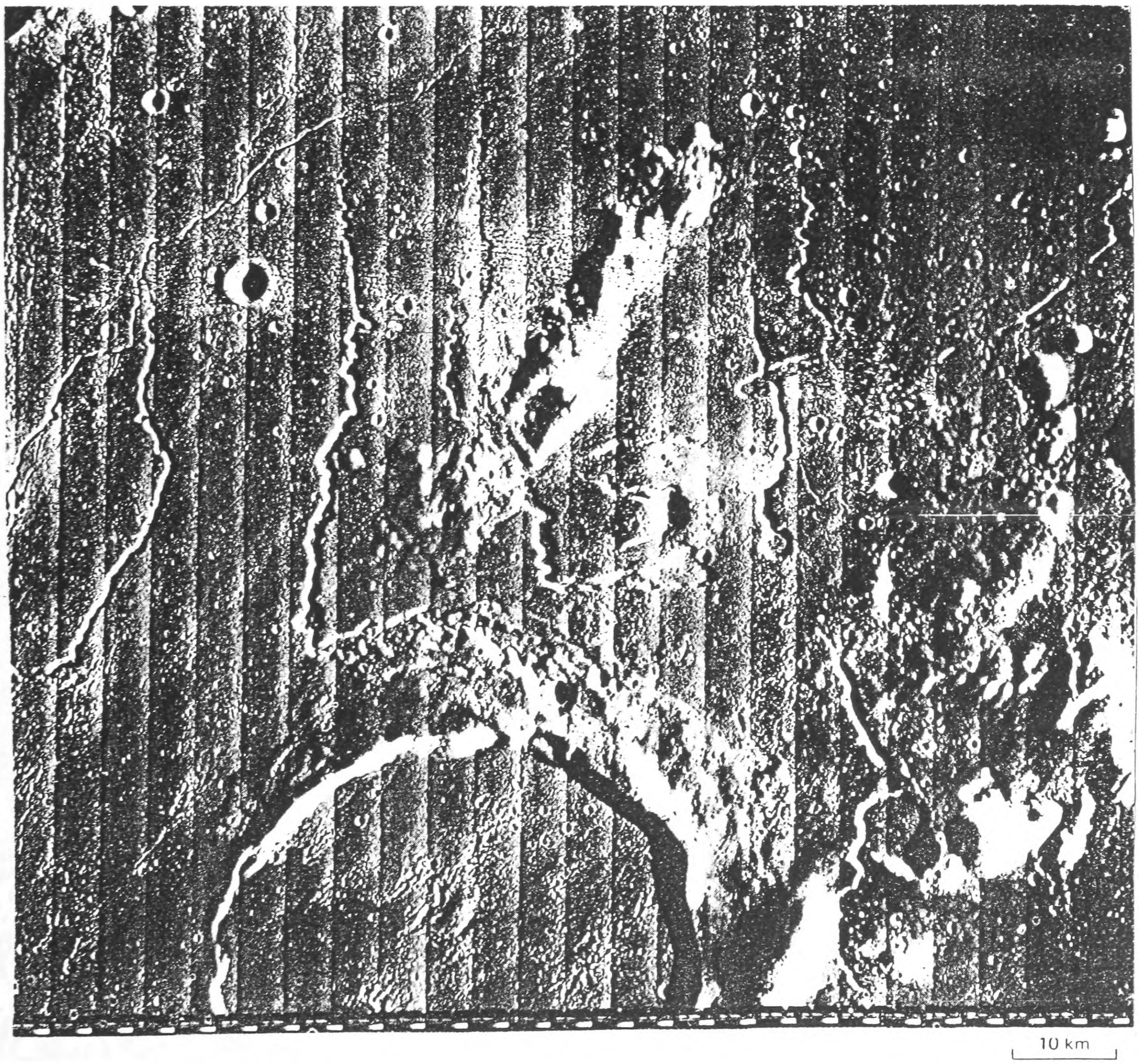


FIGURE 29 HADLEY RILLE - a lunar sinuous rille

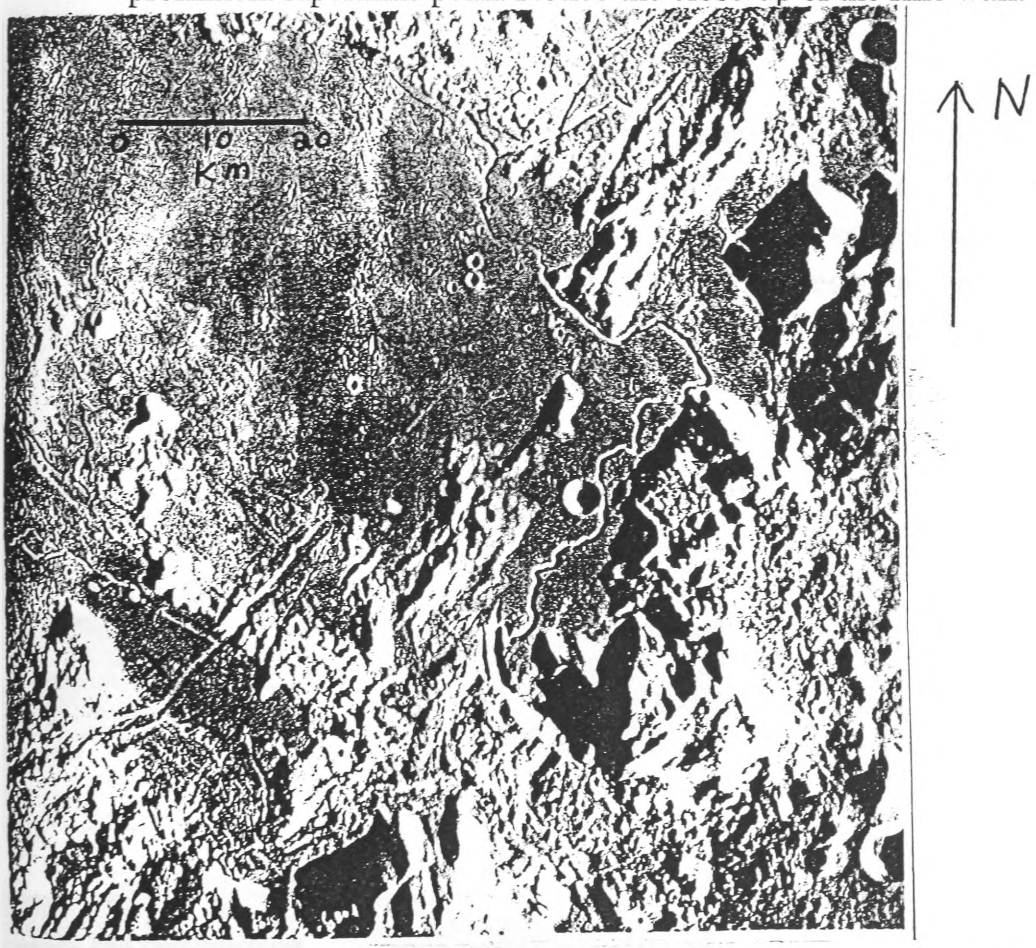
Two views of Hadley Rille,

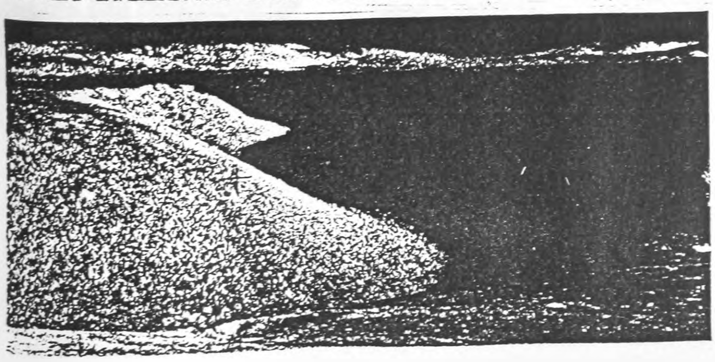
a) Vertical view in Mare Imbrium. This 200 m wide rille starts at the foot of the Apennine Mountains and was probably formed as an open lava channel during the emplacement of the surrounding mare lavas. Some sections may have been bridged to form lava tubes. (NASA-Apollo 15).

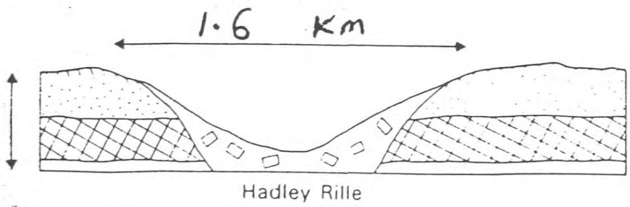
Note the similarity of

- **this rille with the Venusian equivalent back in photo 11.**
- **the probable graben lower left(X) and Venusian graben (photo 18).**

b) Ground view, looking north from the sharpest bend at the base of the prominent Apennine peak. Notice the close-up of the rille wall.







4.3 *The Origin of Lunar Rilles*

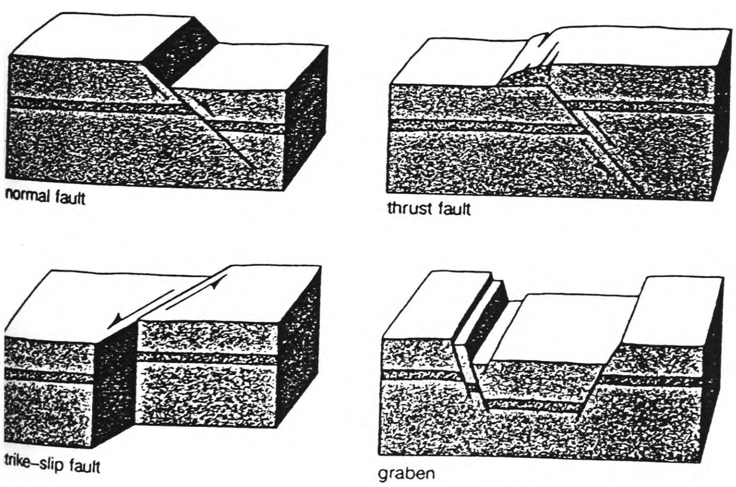
Since there are basically 3 different types of rille one would expect more than one mechanism to be their common cause. This certainly appears to be the case though some original theories tried to explain all rilles in one sweep.

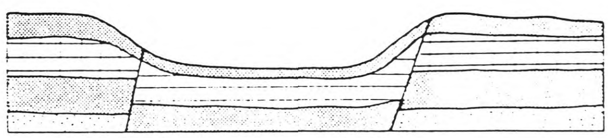
Some theories explaining rilles as watercourses have been all but discounted considering the difficulty of water flowing for any period of time in a vacuum and the problems associated with accounting for the source of this water.

Straight and arcuate rilles can most likely be explained as having formed by some combination of faulting and subsidence as proposed by Quaide et al., 1965. The valley walls in these type of rilles stand at the same elevation, as though they were pulled apart and the floor subsided as a graben. How this may occur is illustrated in Figure 30 below. Straight rilles are parallel or arranged in an echelon pattern. Some intersect, and others form a zigzag pattern similar to that of normal faults on the earth.

The Moon, in fact, abounds with many examples of well developed graben structures as does Venus (Photo 18). When one examines the distribution of graben across the lunar surface, however, a very marked non-randomness in position can be seen (Fielder, 1971). Almost all lunar features identifiable as graben cluster very closely around the edges of the maria and must, therefore, be linked directly or indirectly with these features.

<u>FIGURE 30</u> EXAMPLES OF FAULT STRUCTURES





Typical 'graben-type' rille

It is known that the maria are composed of dense, basaltic rocks and, hence, will tend to sink slowly into the less dense lunar crust under the force of gravity. Under certain conditions this will cause tension and bending in the outer parts of the maria and the surrounding highlands. In other words, conditions that might be ideal for graben formation. In the absence of any obvious updoming, therefore, the lunar rilles cannot be taken as direct evidence of rifting of the type found in East Africa.

Sinuous and Meandering rilles are believed to be either collapsed lava tubes or lava channels by most lunar scientists. Such channels on Hawaiian volcanoes have been noted by Wentworth and MacDonald (1953). Kuiper et al., 1965, have described similaries between the curved course of terrestrial lava channels and the shape of sinuous rilles.

Channels may be formed either at the time that lava is being extruded and flowing downhill to form a surficial pool, or at a time that lava from a surficial pool is draining back below the surface following the eruptive stage. In the latter situation craters which are situated at one end of a rille may be drain-back features.

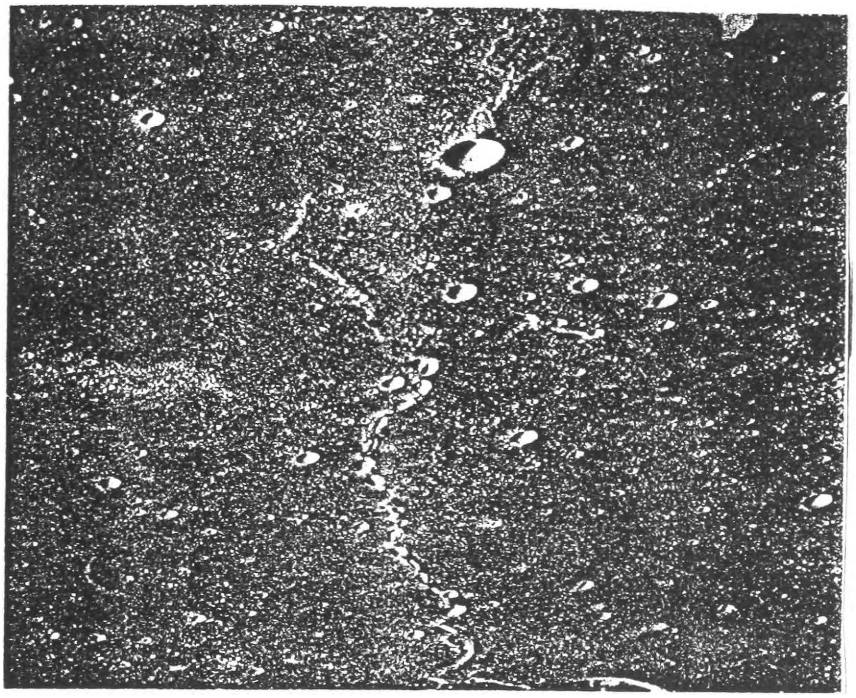
Probably one of the most well-known sinuous rilles is ***Hadley Rille*** (Figure 29) which was visited by Apollo 15. Although it certainly looked like a dried up river bed it has no tributaries and is strictly confined to the mare. Its cross section is V-shaped, but this may just be the result of the impact-induced erosion of the walls and the accumulation of eroded debris (or talus) in the bottom of the rille. The most attractive theory for Hadley Rille's origin is the 'collapsed lava tube' hypothesis (Greeley, 1971; Howard et al., 1972) in which a crust is believed to have formed on top of the molten lava lake. The fluid lava then drained away from beneath this crust out into Mare Imbrium leaving an underground tunnel.

On the Moon these tunnels would have been easily ruptured by meteorite impact and so collapsed to produce sinuous channels. If this collapse was incomplete, as is the case with some sinuous rille, then a row of coalescing craters rather than a continuous channel would have been the result (Figure 31). Notice the similarity of this picture with the Venusian crater chain in photos 17 and 19.

Some sinuous rilles may never have been roofed in the first place but may instead have been open lava channels. The possibility of some sinuous rilles having been formed as a result of gases having vented from fractures was proposed by Schumm and Simons, 1969. This idea was used to explain the frequent occurrence of small craters strung out along rilles. It may explain some of the smaller rilles but certainly not the larger ones.

<u>FIGURE 31</u> LUNAR CRATER CHAIN

This chain of craters and elongate depressions is clearly a sinuous rille in the making. Note the elongated source crater and the wrinkled ridge at its lower end. (NASA).



4.4 *Comparison of Lunar, Terrestrial and Venusian Channels*

Comparisons between lava tubes and channels on the Earth and Venus have already been covered in some detail in this study. How these tie in with the lunar rilles will now be looked at.

Our earlier study revealed many similaries between the Earth and Venus in the way lava was transferred from one point to another. In fact, similar volcanic features such as volcanoes, domes, cinder cones, pit craters and channels are found on both planets. However, there are notable differences, one important one being scale. Things seem to be so much bigger on Venus. Lava channels on Earth tens of km long dwarf those on Venus which may be thousands of km in extent.

It would seem that Venusian lava channels and tubes, at least in regard to size, have more in common with their lunar counterparts than with those on the Earth. This seems surprising when you consider the great contrasting surface conditions. Venus's 90 atm. pressure and boiling temperature (450^{0}C) as against the Moon's near vacuum and much cooler conditions which can be as low as -170^{0}C (night).

Comparing lava channels on the Moon with those of the Earth is inherently difficult because of the difference in scale. For example, the sinuous Pahoehoe lava flow from Devil's Garden in Oregon (U.S.A.) is similar in appearance to lunar meandering rilles, but only being a few km long, is on a much reduced dimension to lunar rilles, which are hundreds of km long. Lunar rilles generally appear to be at least 100 times larger than the majority of terrestrial lava tubes and channels but interestingly, comparable in size to those on Venus.

Based upon calculations and allowing for the reduced gravity on the Moon, the theoretical width of a lunar collapsed lava tube could reach 385 m. But this could reach 500 m considering the greater vesicularity of the lunar lavas.

Furthermore, the degradation following the collapse of the vault could cause lateral slumping which might easily enlarge the sinuous channels by a factor of two, bringing the possible width to one km. The most developed terrestrial lava tubes on the other hand do not surpass widths of 30 m and lengths of 15 - 20 km.

Recall, some Venusian channels were also km wide, with the probable lava tubes candidates having an uncertain width, but hundreds of metres would appear quite possible.

Now since the theoretical limits for maximum lava tube width are exceeded on the Moon (Vallis Schroteri has an "upstream" section 9 km wide) and even more so on Venus (considering the higher gravity) than at least some of the lunar sinuous rilles and channels on Venus, rather than being collapsed lava tubes, must correspond to lava flow channels.

The appearance of Venusian channels hardly makes this conclusion surprising. These flow channels in fact, present at the outset a greater continuity and more sub-parallel flanks. Furthermore, these can have a far greater width than the lava tubes.

Beside size, terrestrial lava tubes do not generally correspond to continuous furrows with parallel rims like those on the Moon but are discontinuous with "bridges" and irregular rims as was the case at Undara. Also, lunar lava tubes have wall slopes of about 30^0 - 40^0, whereas the terrestrial ones often have vertical walls and overhangs (Green & Short, 1971). Of course the inclination of the lunar wall slopes could be caused by degradation, but this condition should be even more evident in the case of terrestrial walls where erosion is more rapid and pronounced. Terraced flooring which occurs in some lunar rilles has not been seen in Venusian lava channels but this may well be due to insufficient resolution. Also, channel branching appears more rare on the Moon and dendritic lava channel patterns seem to be unique to Venus (Photo 13).

As well, many lunar rille have mature meanders and show a clear excavation of the channel. We saw this was also true of a number of Venusian channels (see Photos 10 and 32), however terrestrial lava channels do not have mature meanders. Mature meanders only form when lava has flowed over a period of time and involve both excavation and deposition of material and are analogous to meandering terrestrial watercouses. Also, whereas some lunar rilles show signs of deposition few are clearly visible in Venusian channels at least at the Magellan radar resolution.

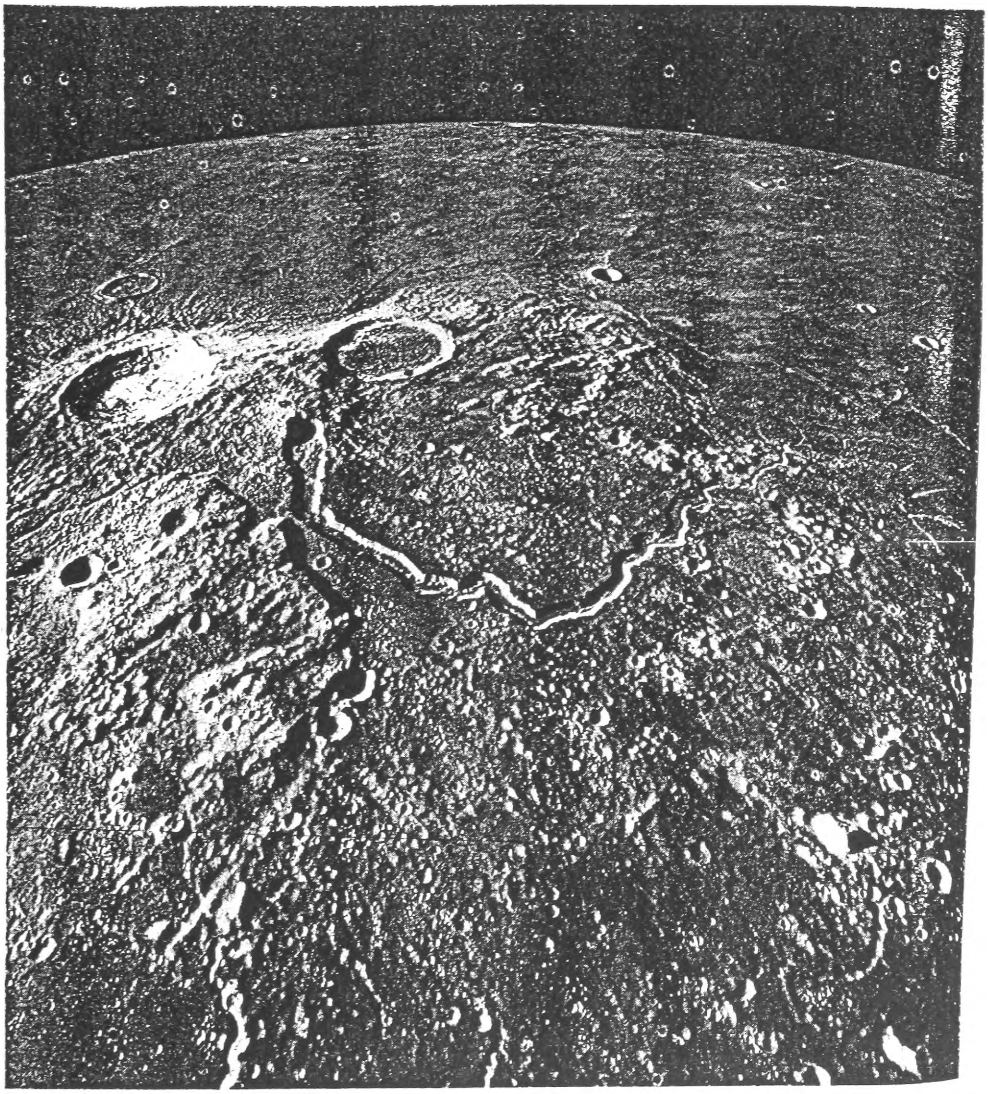
The similarities between lunar and Venusian sinuous rilles can also be seen by comparing the lunar rille in Figure 32 with the Venusian one in Photo 33. Both are similar in shape, comparable in size and show clear excavation of the channel.

This similarity between lunar and Venusian channels is probably due, at least in part, to the common properties of their lava. The behaviour of lava in a vacuum is not well understood but lunar lava, like that of Venus, is believed to be very fluid. Some researches (e.g.O'Keefe, 1962), believe that lunar lavas must be far more fluid than those on Earth. They base this assumption upon the supposed lack of scarps similar to those which mark terrestrial lava flows. This fluid lava, as was mentioned earlier with Venus, would cover large distances on a level terrain, especially if the effusion rate was high, as was the case at Undara.

FIGURE 32 AN EXCAVATING LUNAR SINUOUS RILLE

Oblique view southward across the Aristarchus Plateau showing Schroters Valley, an enormous 'highland' rille more than 150 km long. It consists of a wide outer depression inside which is a normal mare-type sinuous rille which continues off the plateau onto the adjacent mare surface. The fresh crater at the top left is Aristarchus. (NASA Apollo 15).

Note the similarity between Photo 33 (Venus) and this one.



4.5 *Summary of lunar rille*

There are basically three types of lunar rilles.

The straight rilles are usually between one and five km wide and hundreds of km long, unrelated to surface topography, analogous to terrestrial fault grabens. Curved or arcuate rilles are variants of straight rilles, with similar dimensions, and form concentrically to major ring basins e.g. Mare Humorum. Sinuous and Meandering rilles, formed by thermal erosion by flowing lava. Hadley Rille, 1.2 km wide, 270 m deep, and 135 km long, visited by Apollo 15, is the type example.

Sinuous and straight rilles being the most common type on the Moon are equally as common on Venus and are believed to have been formed by similar processes. Favourable terrain, the availability of large amounts of lava and very low viscosity seem to be the most important factors in the large size and distribution of the sinuous rilles on the Moon, as was also the case on Venus.

Lunar rilles are similar in some regards to terrestrial rilles but the vast difference in size and the lack of mature meanders makes them more analogous with Venusian rilles, though the rilles on each planet are unique in their own right, and should be regarded as such.

CHAPTER 5 MARTIAN LAVA TUBES AND CHANNELS

5.1 *Introduction*

Photographs of the martian surface by Mariner 9 clearly show several large shield volcanoes such as Olympus Mons, Ascraeus Mons and Pavonis Mons. A property common to both Mars and the Moon, however, is that volcanic activity appears to be confined almost exclusively to one half of the planet. It has been suggested that large scale planetary convection resulted in a thinner crust in one hemisphere than the other (Fielder & Wilson, 1975).

However, most planetary geologists (Head et al., 1992) believe volcanic activity on Mars, like the Moon, has been dormant for at least several hundred million years. This conclusion has been drawn from the minute rate of change of the surface of these two bodies as evidenced by the number of impact craters.

5.2 *Characteristics of Mars*

Mars has a small atmosphere (7mb) of CO_2 . The polar caps are of water ice with seasonal solid CO_2 . The surface temperature range is between -125^0C and 37^0C. On the whole Mars is very cold. Temperatures at the equator range from a summer high of about 26^0C in the afternoon down to -111^0C just before sunrise. In polar regions temperatures rarely rise above -123^0C all year round (Fielder & Wilson, 1975).

The northern-hemisphere crust is at a much lower elevation being mainly basaltic plains and volcanoes; the southern an ancient cratered terrain, is the older of the two.

Much of the surface reveals the effects of volcanic processes, and several extremely massive shield volcanoes are particularly striking. These rise from the broad Tharsis "bulge" and from a smaller but similar raised area in Elysium, to the west. Mars has the largest volcanoes in the Solar System. Olympus Mons, the largest, rises up to 25 km and has a volume 50 and 100 times that of Mauna Loa, the largest shield volcano on Earth. Extending eastward from Tharsis is the longest valley system on Mars, it is immense and can be traced for a total length of over 4000 km it is called Valles Marineris (Figure 33 and Photo 40). At the western end of this valley lies Noctis Labyrinthus (Figure 34 and Photo 41) which is a huge complex of canyons covering at least 120000 square km (Fielder &Wilson, 1975).

Both volcanic and impact craters also occur on Mars and the largest craters, however they were formed, may date back 4000 million years.

Analysis of samples of surface rocks by two Viking landers revealed their similarity with lunar maria. Also, large amounts of water ice are believed to exist below the surface as permafrost (Fielder & Wilson, 1975).

FIGURE 33 **A MARTIAN GRAND CANYON - Valles Marineris**

This feature appears to be a rift system enlarged by splitting, collapse, and erosion. This view shows chaotic, possibility collapsed terrain and linear faulted canyons at the east end of the system, whose length would easily transverse Australia. The linear canyons are about 150 km wide. (NASA, Viking Orbiter 1).

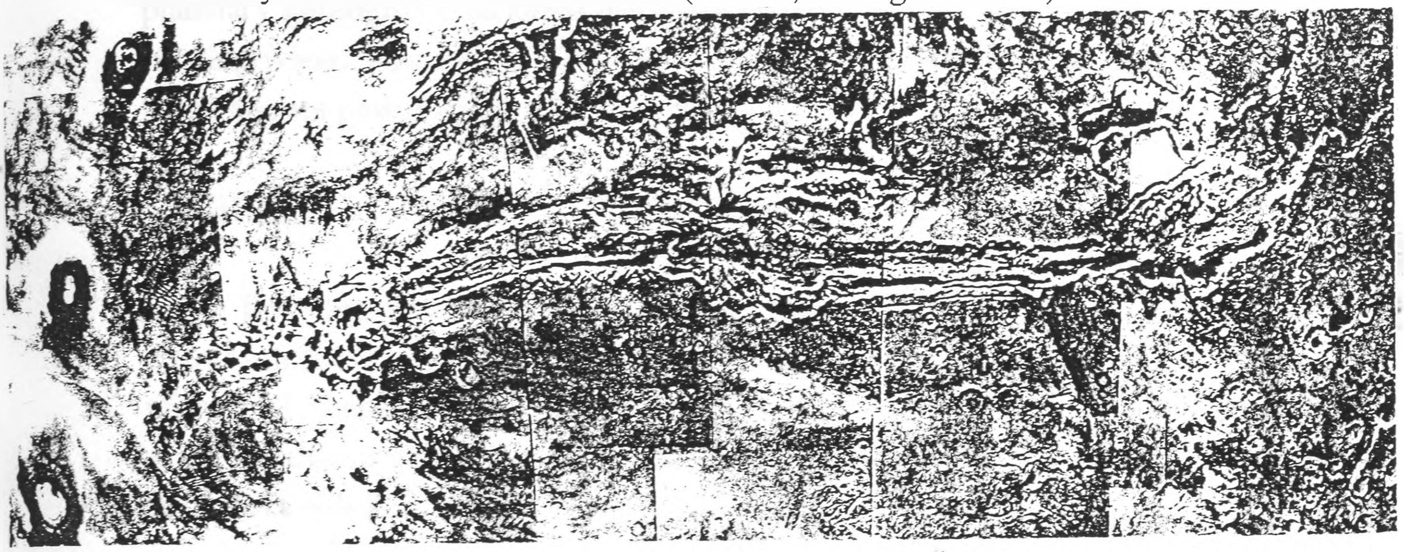
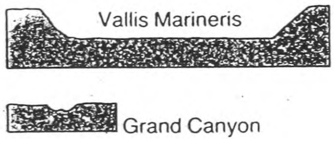
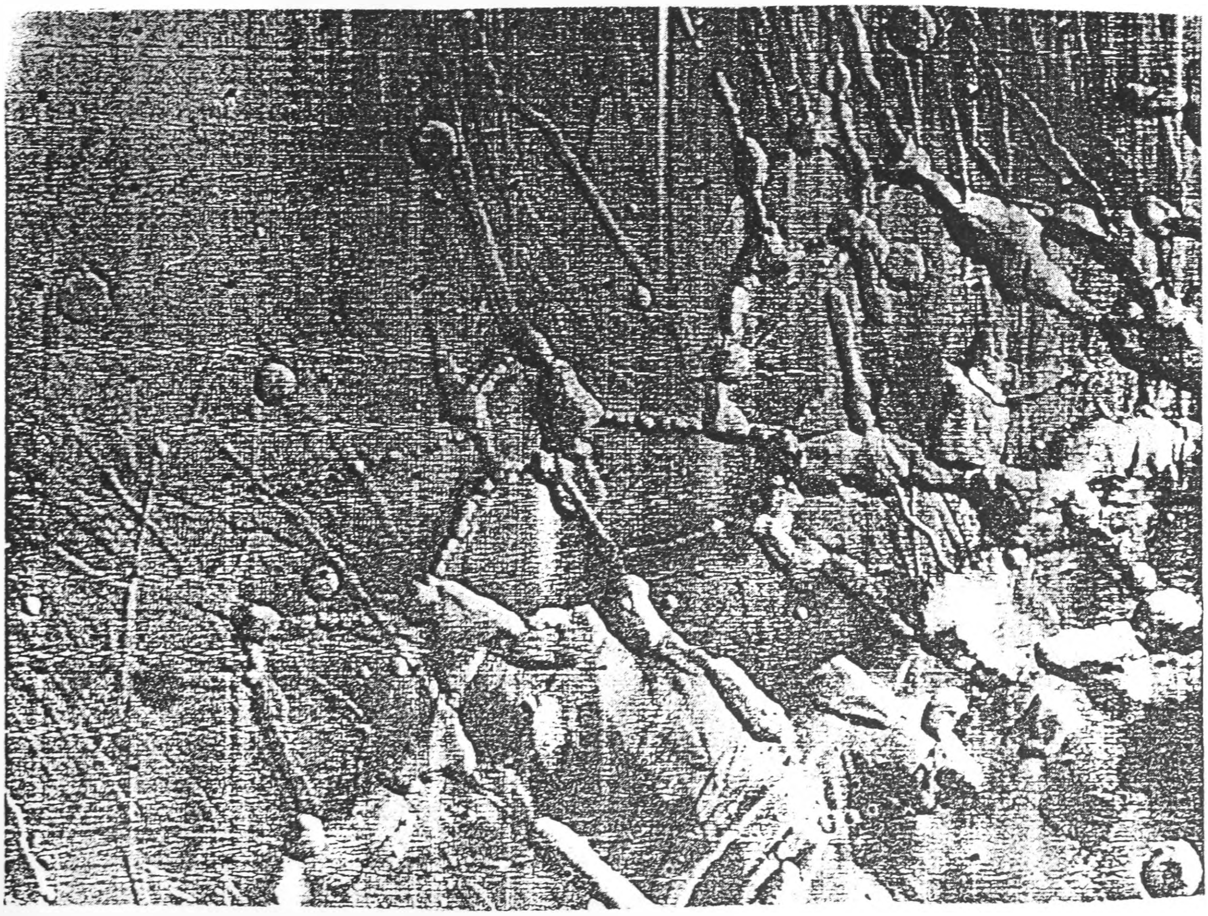


FIGURE 34 **NOCTIS LABYRINTHUS**



This complex section of Noctis Labyrinthus contains interconnecting canyons (graben structures) which is near the centre of the Tharsis dome.
(NASA, Mariner 9).

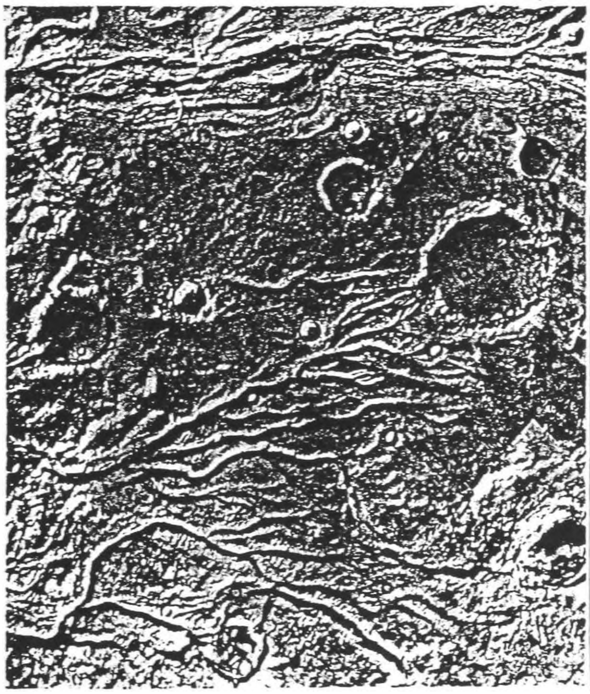


5.3 *Martian Channels*

On November 14, 1971, Mariner 9 became the first spacecraft to go into orbit around Mars. A mapping program began and the high resoluton of a few hundred meters revealed many features including many examples of landforms that looked astonishingly like dry riverbeds (Figure 35 below). After much controversy, most planetary geologists concluded that these features, called channels, were carved by running water. This suggests that the climate of Mars may have been more clement in the ancient past (Fielder & Wilson, 1975).

<u>FIGURE 35</u> MARTIAN CHANNELS

These flow features are believed to have been eroded by running water. Like arroyos in Earth's terrestrial regions, these channels have tributary systems and get wider and deeper in the downhill direction. (NASA, Viking Orbiter). **<u>Note</u>** This widening direction is the opposite to venusian lava channels which may disappear as the lava solidifies (Photo 13 and 33).



Generally martian channels have tributaries, terraced banks, and interlacing mini-channels on their floors, which are called braided channels.

Further study (Carr, 1974) revealed three types of channels:

1) Some are large and have tributary systems that fan out into the martian desert. They originate over a large area (Figure 35).

2) Other large channels originate in rugged, depressed regions (Figure 36). These regions are called **chaotic terrain**, and they resemble collapsed terrain on the Earth produced by the melting of permafrost and the outflow of water.

3) A third type of channel is more abundant but smaller. It occurs as a channel network and is common in the dark, cratered uplands.

All channels are most common in the martian equatorial (warmer) regions and less common in higher latitudes and polar strata (Pieri, 1976). Some of the larger channels empty into broad plains, such as Chryse Planitia, the plain where Viking 1 landed. Here, water seems to have swept across the whole area, eroding craters and cutting through wrinkle ridges (Figure 37).

A few areas, such as shown in Figure 35, exhibit ***dendritic channel*** patterns. The water that probably carved these cannot have originated in a single feature. Some researches have suggested ancient martian rainfall to account for the dispersed water source (Masursky et al, 1977).

The age of the channels is not certain but an extended episode or episodes of channel formation has been placed somewhere between 0.4 and 3.5 billion years ago.

FIGURE 36 CHAOTIC TERRAIN CHANNELS

Martian channel emanating from a collapsed "box canyon" containing chaotic terrain. Note striated flow deposits on the channel floor. The restricted area of source indicates that the origin of the flowing liquid was associated with the formation of the chaotic terrain.(NASA, Viking mosaic).

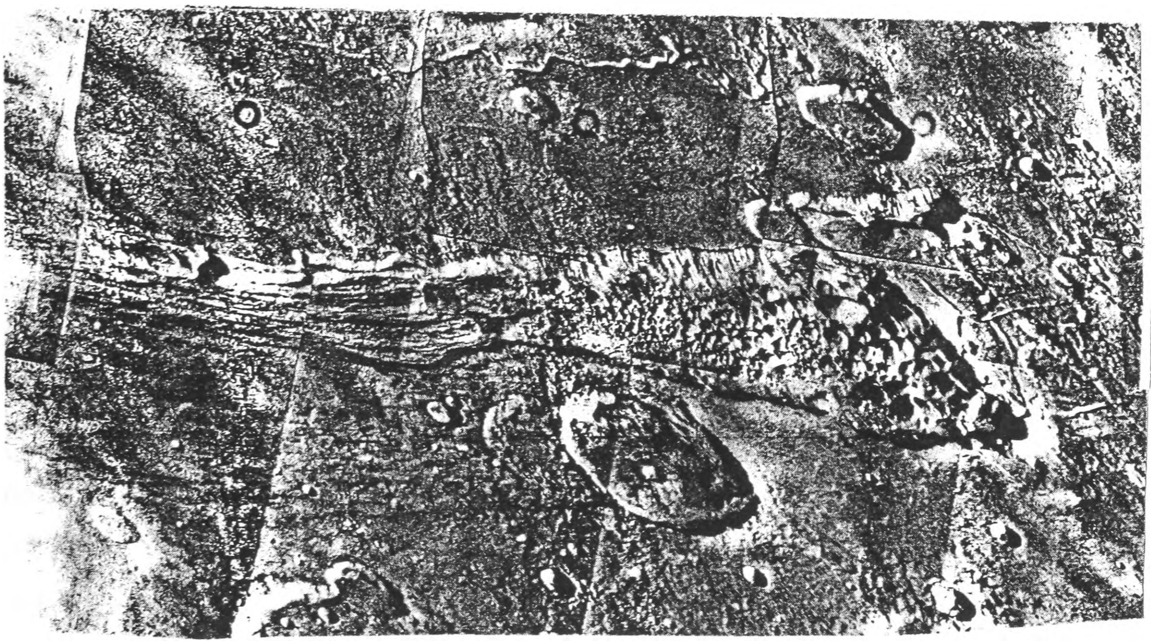
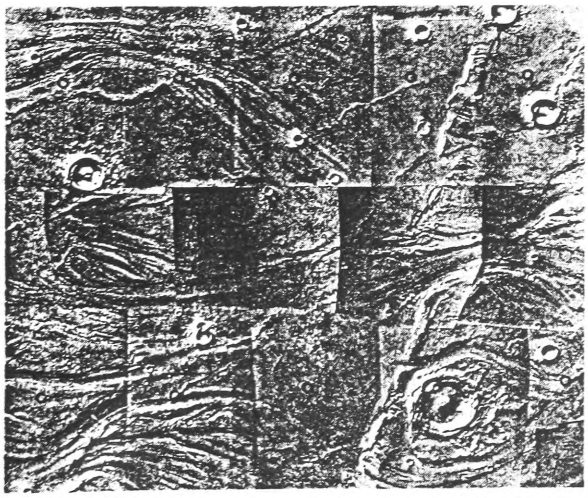


FIGURE 37 A WATER ERODED AREA

Portions of Mars' Chryse Planitia modified by a presumed flow of water.

a) Flow features appear throughout this 200 X 250 km lava plain. Note wrinkle ridges cut by the flow which was from the west (left), where channels empty into the plain from the highlands.

b) Streamlined "islands" left in the wake of preflow craters. The tear-shaped island is 15 X 41 km. (NASA, Viking mosaics).



a

b

5.4 *Martian Canyons*

Visible even on long-distance images of Mars is the great canyon system, which straddles the globe just south of the equator between longitudes 30^0 and 110^0 W. Called Valles Marineris, this 4000 km-long network begins on the east side of the Tharsis Bulge and ends in an immense region of chaotic terrain between Chryse Planitia and Margaritifer Sinus. At its deepest it is some 7 km deep and individual canyons are up to 200 km in width. In the impressive central section, where there are three roughly parallel, interconnecting rifts, the total width is 700 km.

Within the canyon system there is little evidence for the action of running water, although laminated deposits do occur on the floor in places. In the east, where the system ends amongst chaotic terrain, there is ample evidence of fluvial activity in the form of channels.

Faulting seems to have played a major part in shaping the overall form and trend of individual canyons, and where the effects of subsequent erosion are apparent, particularly on the canyon walls, later side-canyons and indentations follow a distinctly linear pattern, typical of fault control.

The main 2400 km-long central canyon section is multiple for its entire length. Parallel to the ESE-WNW -trending canyons are down-faulted blocks and crater chains (Photo 40). These crater chains will be discussed shortly. In the central part of this section are three huge troughs 200 km wide, and the remnants of an eroded plateau separate them from one another.

Landslides have also occurred in places giving the rim of the Valles Marineris canyons a scalloped edge.

PHOTO 40
A section of Valles Marineris. Note the crater chains.

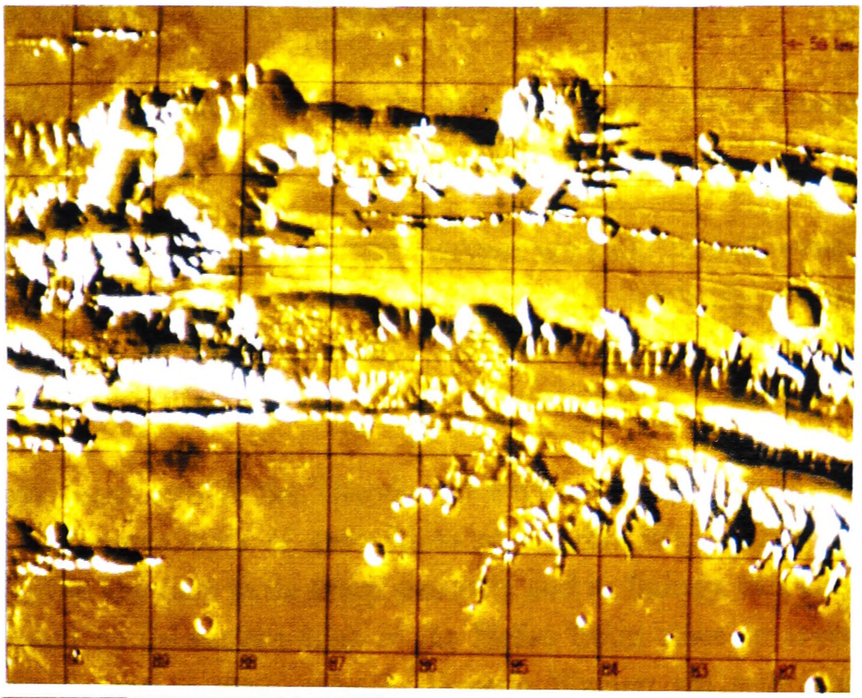


PHOTO 41
A section of Noctis Labyrinthus. **Note** these are depressions.

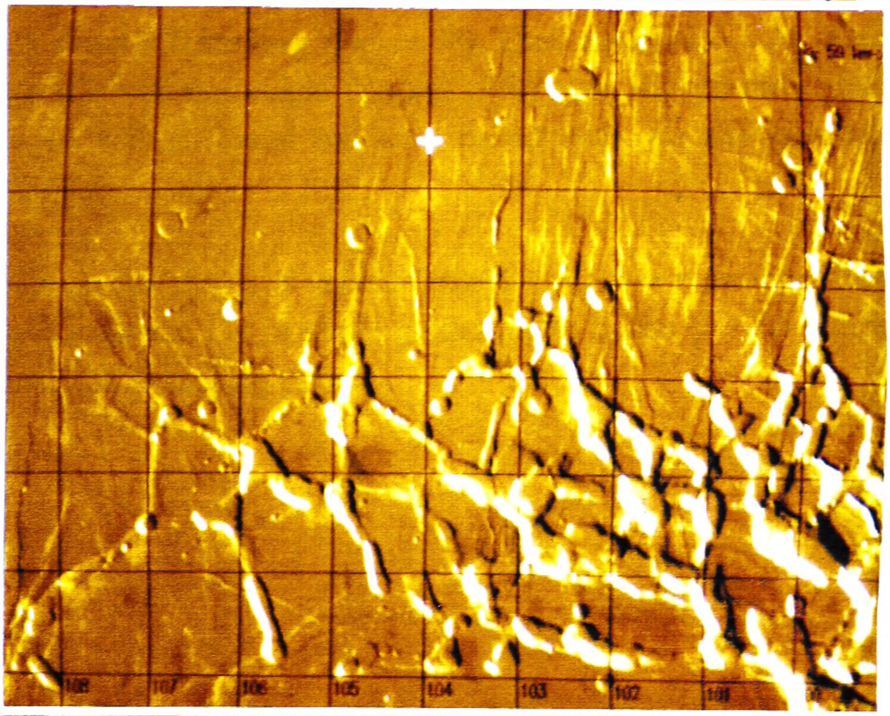
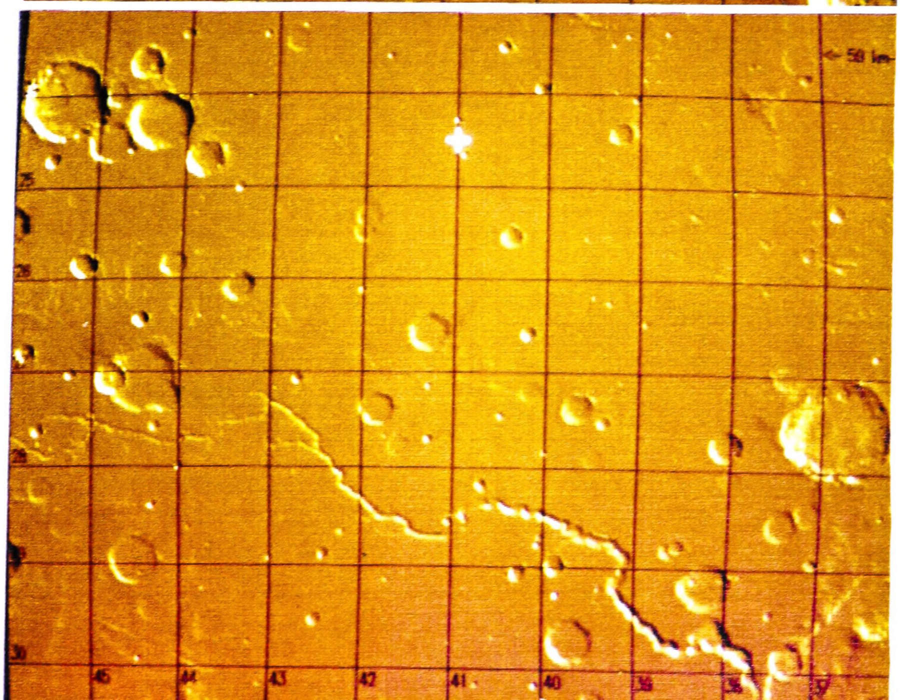


PHOTO 42
A sinuous watercourse



5.5 *Comparison of lunar, terrestrial, venusian and Martian channels*

We certainly know rilles are found on Venus, the Moon and the Earth (although small), but what about Mars?

There is little doubt the vast majority of martian channels are fluid related, even if they are much larger than terrestrial watercourses. However, certainly, as one would expect in areas shaped by volcanic activity, there is little doubt there are also martian lava channels (Carr, 1974).

A few rille-like features occur outside the Tharsis and Elysium volcanic provinces and are ambiguous on grounds both of association and form. We include here Nirgal Vallis, which is rille-like both in its sharp sinuosity and its linkage to a crater source- or sump. Situated on the eastern edge of the Hellas basin close to several degraded volcanic shields and to the south of Hesperia Planum are two large, sinuous channels, each about 500 km long (Figure 38). Their association with other volcanic features suggest a volcanic origin (Potter, 1976) even though their great size invalidates analogies with terrestrial and lunar occurrences, but not venusian which can easily be this size.

Not all of the channels on the slopes of martian shield volcanoes resemble lunar rilles and terrestrial lava channels. For example, gullies on the flanks of Alba Patera (Figure 39) have an irregular branching pattern.

FIGURE 38

A simple, sinuous channel. The occurrence of the channel in a volcanic province, its origin in a crater-like depression, and its downstream decrease in channel size all suggest that it is a lava channel. However, its size greatly exceeds that for terrestrial lava channels and lunar sinuous rilles. (Located 265^{0}W, 32^{0}S)

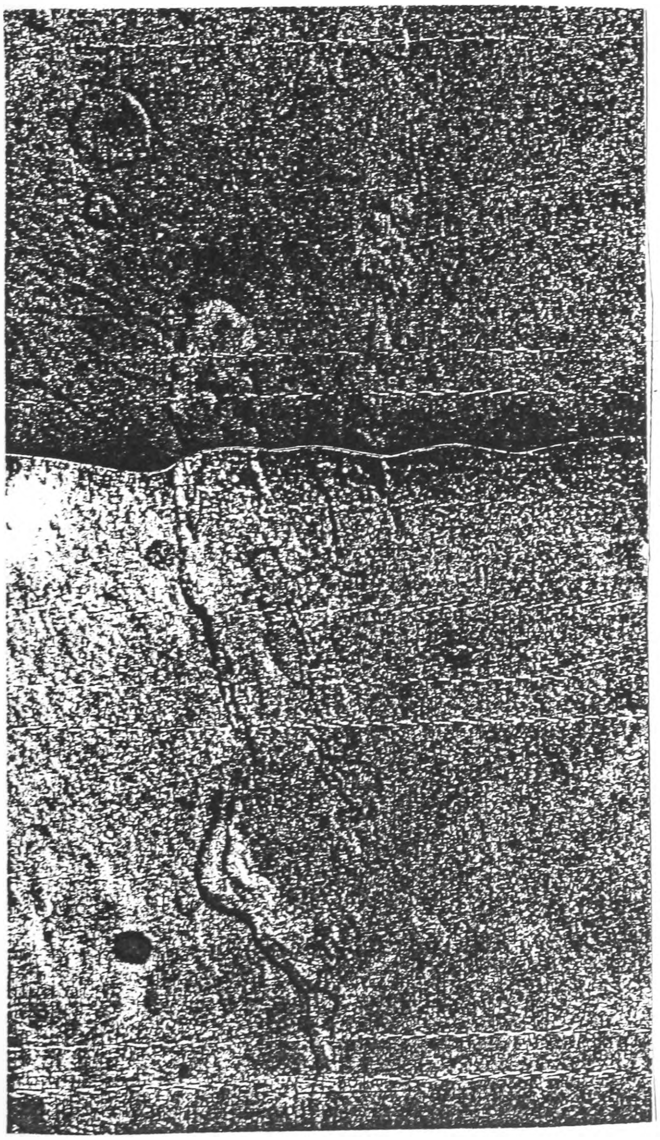
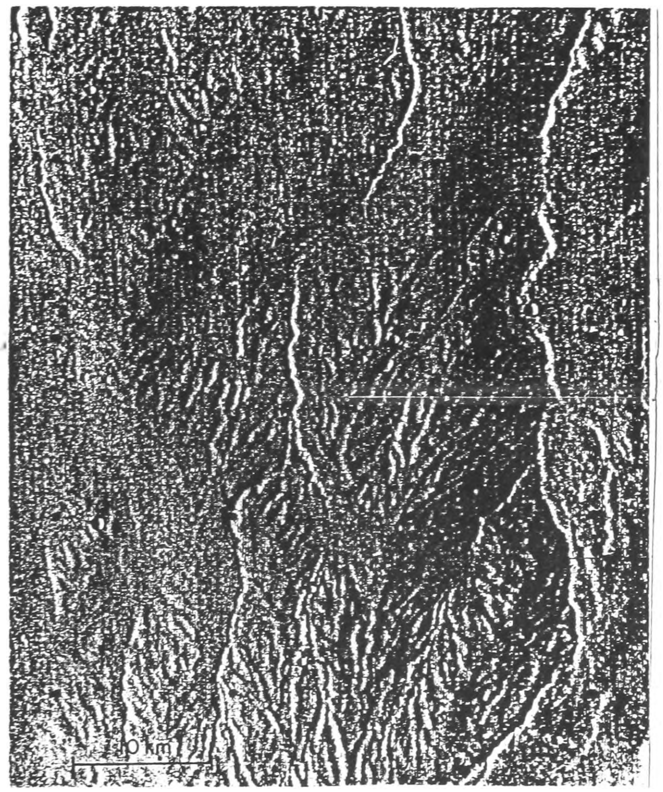


FIGURE 39

Irregularly branching furrows on the flanks of Alba Patera. Features of this sort supply some of the best evidence for surface runoff associated with rainfall. (Located 117^{0}W, 45^{0}N)



Furrows or depressions are also found on Mars as well as on Venus. Their widths range from 2 to 10 km, lengths from 100 to 1000 km. On Venus, they ranged from about 3 km in width to around 20 km in length. It is doubtful that they are related. On Mars their origin is uncertain but some investigators (e.g. Milton, 1973) believe they provide the best available evidence for erosion by rainfall. On Venus, the roundish ones probably resulted from lava ponding, while some others were most likely graben related.

Grabens (Figure 30) are features which have been found in large numbers on the Moon (linear rilles), the Earth, on Venus, and also on Mars (Figure 40). Grabens, on Mars, are thought to be a result of tectonic activity. They are down-dropped blocks a few km in width that in places criss-cross each other, indicating several periods of crustal extension on Mars.

A large proportion of the martian graben appear to be sub-radial to a major upwarp in the Tharsis region (0^0N, 110^0W). Others are strongly influenced by local topography; and a minor, radial system is centered at about 40^0N, 250^0W. These graben do not appear to have been the sites of major volcanism. The Tharsis system of sub-radial graben is not situated on the crest of the upwarp where maximum crustal stretching should have taken place.

Instead, this crest is occupied by two types of feature:

(a) three massive shields and,
(b) an interconnecting canyon-like system. These later features, like the sub-radial graben, probably represent the response of the martian crust to tension.

Figure 41 shows a series of graben on the flanks of two martian volcanoes.

Crater chains are another feature which were found to be very common on Venus, but less common on the Moon and the Earth, and apparently, not as common on Mars either.

The upland surfaces outside the Valles Marineris are marked by elongate, closed depressions aligned parallel to the major canyon segments (Photo 40). Most of these features are clearly small graben (less than about 5 km across), some of which are simple trenches and some of which have associated with them pits that are circular or elongate in plan. Apparently these collapse craters formed along fractures paralleling the rift.

The pits form discontinuous chains, similar to those on the Moon and Venus, along the graben floors, or they may have diameters greater than the width of the graben itself. In some cases the pits are not directly related to visible graben, but alignments roughly parallel graben direction. In the labyrinth, chains of pits of varied sizes suggest that canyons may develop from relatively small pits to large depressions by coalescence of growing pits. This relation between pits and development of the canyons is not so clearly seen elsewhere in the Valles Marineris system, where the closed depressions tend to be much larger and associated with extremely long rifts, such as Coprates. This possibility of pits opening up forming large depressions was discussed as occurring at various locations on Venus (Photo 21 and 29).

On Mars the pits themselves are always deeper than the graben along which they form. One assumes that the graben are a result of tensional fracturing of surface materials. However, the pits, being discrete closed depressions, cannot have such a simple origin.

Similar pits are common in volcanic terrain, for example on the east rift of kilauea, Hawaii, where they are explained by the withdrawal of deep magma, leaving cavities into which surface rocks fall, and Sharp (1973) has suggested this origin for the Valles Marineris pits.

However, no evidence has been found for volcanism contemporary with the rifting or erosion of the canyons, and to invoke a volcanic mechanism for pit formation would involve an improbable style of volcanism where intrusion occurred repeatedly close to the surface but eruption was absent.

Two other mechanisms might cause the collapse:

1) The removal of some other material such as subsurface ice which was also suggested by Sharp (1973). While this is possible, it would necessitate the removal of extremely large volumes of segregated ground ice.

2) A second possibility is that the faults bounding the graben are not simple normal faults but that beneath some graben the faults splay out at depth to form reverse faults, (Figure 30), thereby allowing substantial collapse at the surface outside the intersection of the fault plane with the ground surface.

There are a number of examples in the Valles Marineris system of almost closed, large depressions with blunt ends associated with, but wider than, graben. Extrapolating from the smaller pits, one finds that it is at least possible that the larger valleys have been broadened not only by normal erosive processes but also by collapse similar in character to that which has produced the smaller pits. This process of pit formation on graben is important to an understanding of the tectonics of Mars and also of the Moon, where, for example, the pits on the Hyginus Rille are again not directly related to any observed volcanic activity.

FIGURE 40 **PROBABLE MARTIAN GRABEN FEATURES**
(Mariner 9, NASA)

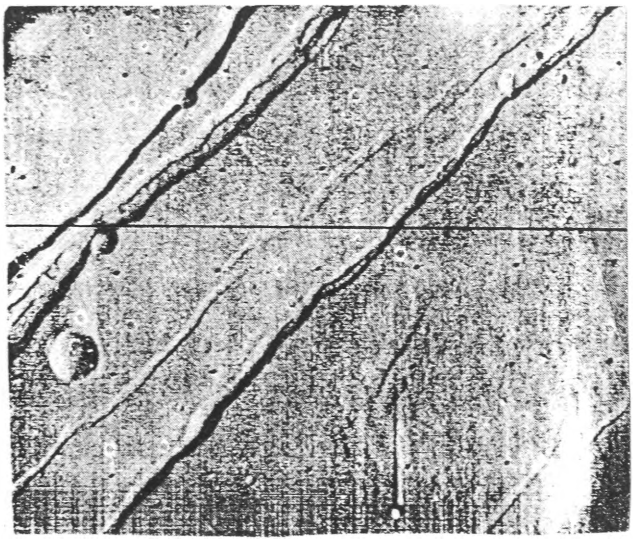
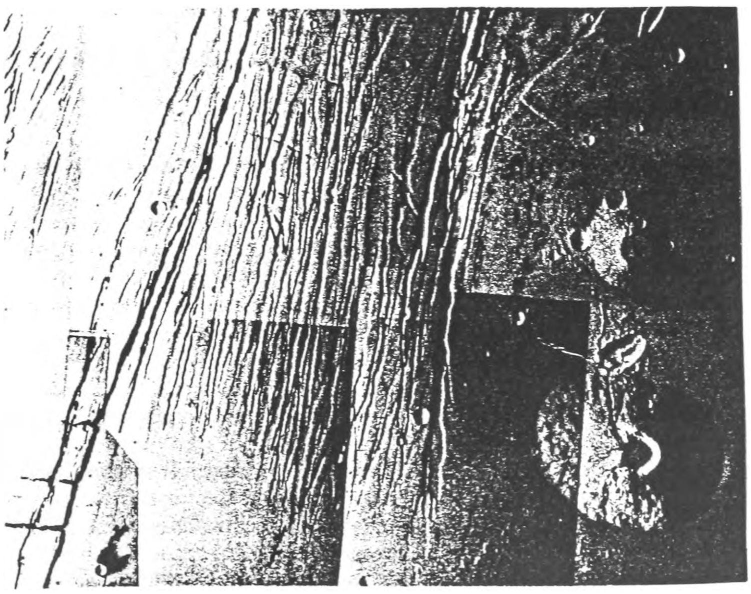


FIGURE 41 **A SERIES OF PARALLEL GRABEN**

A lineament family of faults and grabens beside two volcanoes on the north flank of Mars' Tharsis volcanic field. These and other lineaments run roughly radial to the Tharsis complex and may have been produced by updoming (Wise et al, 1979). Photo width is about 600 km. (NASA, Viking Orbiter 1 mosaic).



5.6 *How do the martian and lunar channels compare to one another?*

Martian channels, regardless of their origin, are far larger than lunar channels (rilles). Martian channels may be thousands of km long and tens of km wide. The deposition of eroded material from these channels is also more evident on the martian landscape.

Martian and lunar channels are both present in large numbers, are usually continuous along their entire length, and both resemble terrestrial watercourses. However, martian channels are often more complex in structure. This complex appearance is particularly evident when martian channels exhibit branching and dendritic patterns as seen in Figure 39. Generally, martian channels have tributaries, whereas lunar ones do not. However, both often have terraced banks.

Also, although straight and sinuous channels are common on Mars, channels that meander to the extent of the lunar ones appear less common. This can probably be related to their origin (flowing water or lava).

Most lunar rilles tend to narrow away from their source and many examples of channels narrowing downslope are also evident on lunar photographs (Figures 28 and 32) which provide evidence for a lava flow origin, as previously mentioned. However, the vast majority of martian channels increase in size downslope most likely indicating a water flow origin.

A notable difference between lunar and martian channels is where they are found and their point of origin. As stated previously, most sinuous rilles avoid the ridges and clearly tend to deviate from the highlands. Straight and arcuate rilles cluster around the edges of the maria. All martian channels on the other hand, are most common in the martian equatorial regions and less common in higher latitudes and polar strata.

Some martian channels tend to originate over a large area (Figure 35), others in rugged, depressed regions called chaotic terrain (Figure 36). Still some others, as with the smaller channels, occurs as a channel network and is more common in the dark, cratered uplands.

A number of lunar channels appear to originate from craters (Figures 31 and 32), whereas this would appear to be far less common on Mars.

5.7 *Summary of Martian Channels*

The surface of Mars reveals volcanic activity has certainly occurred sometime in the past and many volcanic features such as volcanoes are still visible.

Although the large number of channels present on Mars are almost certainly due to the action of fluids, at a more hospitable time in martian history, at least some are lava channels. The water channels are far greater in size than terrestrial watercourses and indicate mammoth floods occurred at times in the past, probably being caused by the melting of permafrost by volcanic activity. These watercourses being formed by the action of water, thus, cannot be seriously compared to lunar, terrestrial, lunar or venusian lava channels.

The martian channels and lunar rilles are both a common surface feature, resemble terrestrial watercourses in appearance, and are usually continuous along their length. They differ most importantly in their size, point of origin, complexity and origin.

Grabens are common on Mars and are similar in shape and size to those found on other terrestrial bodies.

Crater chains do not appear to be quite as common on Mars as on the Moon and certainly Venus has more, but most can be attributed to collapse of surface material, although some may be due to gas venting as is the case with the Moon.

CHAPTER 6 CONCLUSION AND PROSPECTS

We have seen throughout this study the importance of volcanic activity in shaping a planet's surface. Over time the surface of the planet or moon is further modified by the forces of erosion.

The rate of erosion is believed to be extremely low on the Moon due to the lack of any appreciable atmosphere. Some degradation will result from meteor bombardment and thermal weathering due to temperature variations (Fielder, 1971). On Venus the lack of running water and low surface winds give all the indications that surface erosion is small, although, chemical erosion may be significant (NASA, mission data). The surface of Mars is thought to be very ancient as indicated by the abundance of impact craters, although, dust storms will have a small scale affect (Fielder, 1971). We know erosion is quite high on the Earth and it's surface is the youngest of all the inner planets (Hartmann, 1993).

The fact that erosion occurs on these bodies at different rates makes any surface analysis all the more difficult.

It has become clear that although the Moon, Mars, Venus and the Earth are very distinct bodies and have contrasting surface conditions[4] similar structures are found on each. This is quite surprising when one recalls, for example, that lava is believed to be very fluid both under the intense pressure of the venusian atmosphere and also the near vacuum of the Moon. These contrasting conditions, however, has also led to different manifestations of these structures. For example, crater chains and indentations exist on the Moon, Mars, Venus and the Earth but appear more numerous and bigger on Venus. Lava channels, similarly, are much more extensive in size on the Moon and Venus.

[4] Surface conditions here include gravity as well as atmosphere.

The existence of grabens, crater chains, rifting and most probably lava tubes on the Earth, Venus, the Moon and Mars have now been firmly established and reasonable comparisons made. Nearly all the information about Mars and Venus has been obtained by space probes operating at limited resolutions. Few landings have occurred on these planets none of which were manned and no samples have been returned to the earth, as was the case with the Moon, giving us no direct access to material from these planets.

In the future when space probes equipped with more sophisticated equipment make more thorough observations, conduct more detailed experiments, and maybe even collect samples, a more complete picture will emerge. For the moment, however, the data jigsaw has barely started.

APPENDIX A CRATER CHAIN STATISTICS (Table 1)

NO.	No. in Chain	Length (kms.)	Av. Crater Diameter (meters)	Follows Faults (Yes\No)	*Curvature* (Straight\Curved)	Parallel to Other Chains (Yes\No)	Other Chains Present (yes\No)
1	6	4.5	700	N	St.	Y	Y
2	4	6.5	1200	N	St.	Y	Y
3	8	15.3	500	N	St.	Y	Y
4	30	30	200	Y	St.	-	N
5	10	8.4	500	N	St.	Y	Y
6	20	22.8	500	N	St.	Y	Y
7	7	8	300	Same Direction	St.	Y	Y
8	10	5	300	Same Direction	St.	Y	Y
9	12	13.7	1000	N	St.	Y	Y
10	6	8	1000	N	St.	Y	Y
11	8	12.6	1500	N	St.	Y	Y
12	6	6.7	1000	Same Direction	St.	Y	Y
13	8	14	1000	Same Direction	St.	Y	Y
14	20	45.5	200	Y	St.	Y	Y
15	15	47.5	1300	Y	St.	Y	Y
16	10	12.4	800	-	St.	Y	Y
17	12	13.1	200	-	St.	Y	Y
18	8	8.6	300	-	St.	Y	Y
19	12	13.9	300	-	St.	Y	Y
20	40	80	300	Y	St.	-	N
21	6	4.7	600	-	St.	Y	Y
22	10	21.9	500	-	St.	Y	Y
23	12	14.4	500	-	St.	Y	Y
24	20	25	500	-	St.	Y	Y
25	4	2.2	500	-	St.	Y	Y
26	15	44	600	-	St.	-	N
27	10	7.7	400	-	St.	Y	Y
28	6	13.1	1300	-	St.	Y	Y
29	40	73	400	Y	Curv.	Y	Y
30	40	58	400	Y	Curv.	Y	Y
31	4	3.5	900	N	St.	Y	Y
32	12	12.3	300	-	St.	N	Y
33	16	14	400	-	Slight Curve	-	N
34	15	14.6	400	-	St.	-	-
35	12	12.5	300	-	St.	-	-
36	8	5.1	200	-	St.	Y	Y
37	35	34.8	200	-	St.	Y	Y
38	12	13.4	500	-	St.	Y	Y
39	12	22	500	Y	Curv.	Y	Y
40	6	4.4	300	Y	Curv.	Y	Y
41	10	7.6	400	N	St.	N	N
42	12	12.7	300	N	St.	Y	Y
43	12	5.3	200	N	St.	Y	Y
44	60	117	300	N	St.	-	-
45	10	7.6	300	Y	St.	N	N
46	20	108	1500	-	St.	Y	Y

47	25	40	1100	-	St.	Y	Y
48	15	43	1000	-	St.	Y	Y
49	12	13.7	800	-	St.	-	-
50	30	39	600	-	St.	-	-
51	6	6.8	1000	-	St.	Y	Y
52	3	2.6	800	-	St.	Y	Y
53	7	10.8	1200	-	St.	Y	Y
54	8	7.4	500	-	St.	Y	Y
55	12	12.6	500	-	St.	Y	Y
56	10	7.4	400	-	St.	Y	Y
57	10	10.1	300	-	St.	Y	Y
58	25	19.7	400	-	St.	Y	Y
59	30	30.2	400	-	St.	Y	Y
60	20	24	500	-	St.	Y	Y
61	15	18.5	600	-	St.	Y	Y
62	10	9.7	500	-	St.	Y	Y
63	12	20.6	400	-	St.	Y and N	Y
64	12	19.1	200	-	St.	Y and N	Y
65	20	20.3	500	N	St.	Y	Y
66	25	30.9	400	N	Straight than curves	Y	Y
67	14	14.1	600	Y	St.	Y	Y
68	8	9	400	Y	St.	Y	Y
69	6	6.8	400	Y	St.	Y	Y
70	24	46	500	Y	St.	-	N
71	20	42	300	Y	St.	-	N
72	20	77	200	N	Curv.	-	-
73	35	32	400	N	Curv.	-	-
74	35	31	300	Y	Curv.	-	-
75	3	8.3	1300	Y	St.	-	N
76	6	13.7	1000	N	St.	Y	Y
77	10	14	300	N	St.	Y	Y
78	20	12	150	Y	St.	Y	Y
79	25	18	150	N	St.	Y	Y
80	6	7	200	N	St.	Y	Y
81	14	11.4	200	Y	St.	N	Y
82	12	18.3	200	Y	St.	Y	Y
83	14	12	200	N	St.	Y	Y
84	6	16	500	N	St.	Y	Y
85	10	16	200	N	St.	Y	Y
86	10	14.7	200	Y	St.	Y	Y
87	20	16	300	N	St.	Y	Y
88	4	6	800	N	St.	Y	Y
89	20	20	300	Y	St.	Y	Y
90	6	16	1000	N	St.	Y	Y
91	25	42	1300	N	St.	N	N
92	12	13	200	Y	Slight Curve	-	-
93	12	10	300	N	St.	Y	Y
94	10	11	300	N	St.	N	Y
95	20	18	200	N	St.	N	Y
96	12	24	1000	Y	St.	Y	Y
97	6	6.6	300	N	St.	N	N
98	12	23.7	900	Y	St.	Y	Y

99	6	5.5	300	Y	St.	Y	Y
100	15	41.7	**1400**	Y	St.	N	N
101	15	35	1000	N	St.	Y	Y
102	6	3.3	200	N	St.	Y	Y
103	8	8.3	200	Same Direction	St.	Y	Y
104	6	10.6	1100	N	St.	Y	Y
105	8	6.7	120	Y	St.	Y	Y
106	7	4.8	200	N	St.	Y	Y
107	9	11	1000	Same Direction	St.	Y	Y
108	12	12.4	700	N	Curv.	-	-
109	12	9.8	200	N	St.	Y	Y
110	2	2.3	1100	N	St.	Y	Y
111	12	19.4	200	N	Slight Curve	Y	Y
112	30	27	150	N	St.	Y	Y
113	12	9	150	N	St.	Y	Y
114	12	14.6	150	Y	St.	Y	Y
115	30	23	150	Y	Slight Curve	Y	Y
116	7	12.5	600	Y	St.	-	-
117	20	51	400	N	St.	-	-
118	20	25	500	N	St.	Y	Y
119	8	15	1000	N	St.	Y	Y
120	20	56	500	N	St.	Y	Y
121	12	24	500	N	St.	Y	Y
122	15	20	800	Y	St.	Y	Y
123	30	60	400	N	Slight Curve	Y	Y
124	14	35	400	N	St.	Y	Y
125	30	50	200	N	St.	Y	Y
126	30	32	200	Y	St.	Y	Y
127	50	**86**	300	N	St.	-	-
128	12	13	**1300**	Y	St.	Y	Y
129	8	12	500	Y	St.	Y	Y
130	12	75	900	N	St.	Y	Y
131	20	45.8	900	Y	St.	-	-
132	5	15.2	**1700**	Y	St.	Y	Y
133	4	3.8	500	Y	St.	Y	Y
134	6	12.7	500	Y	St.	Y	Y
135	8	5.9	300	N	Slight Curve	-	-
136	8	16.5	700	Y	St.	-	-
137	15	25.4	200	Y	St.	Y	Y
138	12	13	200	Y	St.	Y	Y
139	20	33	300	Y	St.	Y	Y
140	6	6.8	300	N	St.	Y	Y
141	55	50.8	300	N	St.	Y	Y
142	10	15.8	300	N	St.	Y	Y
143	12	14.2	800	N	St.	Y	Y
144	12	11.9	300	Y	St.	N	N
145	6	15.4	600	Y	St.	Y	Y
146	6	12.5	600	N	St.	Y	Y
147	12	16.7	700	N	St.	Y	Y
148	6	5.6	300	N	St.	Y	Y
149	6	4.7	300	N	St.	Y	Y
150	30	24.7	400	N	St.	Y	Y

151	12	11.7	700	N	St.	Y	Y
152	6	11.4	400	N	St.	Y	Y
153	12	11.9	600	Y	St.	Y	Y
154	8	10.5	650	Y	St.	Y	Y
155	5	2.5	300	Y	St.	Y	Y
156	4	4.4	400	Y	St.	Y	Y
157	6	23.5	1100	Y	St.	Y	Y
158	3	6.6	1100	N	St.	Y	Y
159	40	43.4	500	Y	St.	Y	Y
160	40	36.5	400	Y	St.	Y	Y
161	40	67	400	Y	St.	Y	Y
162	20	23.3	300	Y	St.	Y	Y
163	8	13.6	1100	Y	St.	Y	Y
164	6	12.5	1000	Y	St.	Y	Y
165	12	14.2	200	Y	St.	Y	Y
166	20	9.7	300	N	Slight Curve	Y	Y
167	8	9.8	800	Y	St.	Y	Y
168	6	15.6	**1300**	N	St.	N	N
169	8	8.4	600	Y	St.	Y	Y
170	30	66.3	**700**	N	St.	Y	Y
171	10	8.9	500	N	St.	Y	Y
172	6	4.1	500	N	St.	**N**	Y
173	30	30.1	400	N	St.	Y	Y
174	30	32.8	300	Y	St.	Y	Y
175	20	31.4	500	Y	St.	Y	Y
176	12	10	200	Y	St.	Y	Y
177	10	15.8	700	N	St.	Y	Y
178	15	13.2	450	Y	Slight Curve	Y	Y
179	14	18.3	400	Y	St.	Y	Y
180	25	23.1	300	N	Curv. (circular)	-	-
181	30	58.5	300	Y	Curv.	-	-
182	30	**78.5**	400	Y	St.	Y	Y
183	9	11.5	700	N	St.	N	N
184	20	20	400	Y	Slight Curve	-	-
185	7	8.6	600	N	St.	Y	Y
186	20	18.8	300	N	Curv.	Y	Y
187	12	7	300	N	Slight Curve	N	Y
188	12	13.3	400	N	St.	N	Y
189	8	11.1	600	N	Curv.	N	Y
190	15	26.3	400	N	St.	N	Y
191	12	7.7	300	Y	St.	N	Y
192	20	9.4	200	Y	St.	N	Y
193	15	13.7	200	Same Direction	St.	Y	Y
194	50	**220**	200	Y	Slight Curve	N	Y
195	15	**79.2**	400	N	St.	N	N
196	35	**80.4**	300	Y	St.	Y	Y
197	15	40	1200	Y	St.	Y	Y
198	14	41.6	400	Y	St.	Y	Y
199	12	14.5	600	Y	St.	N	Y
200	20	15	300	N	St.	N	Y
201	20	11.9	200	N	St.	Y	Y
202	35	25.5	200	Y	Slight Curve	Y	Y

203	30	59.4	300	N	Slight Curve	N	N
204	10	9	600	Same Direction	St.	Y	Y
205	30	45	300	N	Slight Curve	N	N
206	30	42.5	800	Same Direction	Slight Curve	Y	Y
207	4	6.5	1000	N	St.	-	-
208	12	31.5	600	Y	St.	-	-
209	10	69.2	750	Y	St.	N	N
210	30	41	900	Y	Curv.	N	Y
211	20	53	1000	Y	St.	N	Y
212	12	18.6	500	Y	St.	Y	Y
213	10	10.2	450	Same Direction	St.	N	Y
214	9	25	700	Same Direction	St.	N	Y
215	8	20.9	500	Same Direction	St.	N	Y
216	20	23.3	250	N	St.	N	N
217	10	7.8	300	Same Direction	St.	Y	Y
218	8	4.7	350	Same Direction	St.	Y	Y
219	9	9.2	400	Same Direction	St.	Y	Y
220	6	4.8	350	Same Direction	St.	Y	Y
221	10	31.1	600	Same Direction	St.	N	N
222	8	18.7	1400	Same Direction	St.	Y	Y
223	20	45	600	Same Direction	St.	Y	Y
224	12	16.1	600	Same Direction	St.	Y	Y
225	20	57.3	400	Y	St.	Y	Y
226	20	60.6	600	Y	St.	Y	Y
227	20	56.3	700	Y	St.	Y	Y
228	30	74	700	Y	St.	Y	Y
229	12	26	800	N	St.	Y	Y
230	35	107.2	1200	Same Direction	St.	Y	Y
231	20	29.7	400	Same Direction	St.	Y	Y
232	13	8.1	300	N	St.	N	Y
233	35	151.8	350	Y	St.	N	N
234	45	60.5	300	Y	St.	Y	Y
235	45	72.3	300	Y	St.	Y	Y
236	10	20.4	800	Y	St.	N	N
237	10	26.6	300	Y	St.	Y	Y
238	25	48.7	1200	N	Bent	N	Y
239	12	19.1	1100	N	St.	Y	Y
240	12	15.5	700	Same Direction	St.	Y	Y
241	10	6.4	450	N	Bent	N	N
242	6	9.2	500	N	St.	N	Y
243	5	3.2	400	N	St.	Y	Y
244	7	3.9	300	N	St.	Y	Y
245	30	52.4	1000	N	St.	N	Y
246	12	18.6	600	N	St.	Y	Y
247	21	47.4	1000	Y	Bent	Y	Y
248	40	33.9	400	Y	St.	Y	Y
249	15	12.4	400	Y	St.	Y	Y
250	20	34.6	600	N	St.	N	N
251	30	35	500	Y	St.	Y	Y
252	5	3.6	600	N	St.	N	N
253	16	46.6	1500	Same Direction	St.	Y	Y
254	7	7.1	700	Y	St.	Y	Y

255	25	58.2	600	Y	St.	N	N
256	20	36.8	400	Y	St.	Y	Y
257	8	3.6	250	Y	St.	Y	N
258	30	37.6	300	Same Direction	St.	N	N
259	30	38.5	950	N	St.	N	N
260	15	14.3	700	Same Direction	St.	Y	Y
	Av=15.8	**Av=25.2**	**Av=542.6**				
	Med=12	**Med=15**	**Med=400**				
	Range	**Range**	**Range**				
	2 --> 60	**2.2-->**	**? -->2 km**				
		220km					

TABLE 2 CRATER CHAIN DIAMETER

APPENDIX A(Table 2)		
CRATER DIA. CLASS	FREQUENCY	CUMULATIVE FREQUENCY
UP TO 200	7	7
200 - 300	39	46
301 - 400	53	99
401 - 500	40	139
501 - 600	30	169
601 - 700	29	198
701 - 800	14	212
801 - 900	10	222
901 - 1000	7	229
1001 - 1100	17	246
1101 - 1200	7	253
1201 - 1300	4	257
1301 - 1400	6	263
1401 - 1500	2	265
> 1500	5	270

TABLE 3 CRATER CHAIN LENGTH

LENGTH CLASS (KMS)	FREQUENCY	CUMULATIVE FREQUENCY
up to 10 kms	68	68
10 - 20	93	161
21 - 30	27	188
31 - 40	21	209
41 - 50	20	229
51 - 60	13	242
61 - 70	3	245
71 - 80	9	254
81 - 90	1	255
91 - 100	0	255
101 - 110	2	257
111 - 120	1	258
121 - 130	0	258
131 - 140	0	258
141 - 150	0	258
> 150	2	260

CHART 1

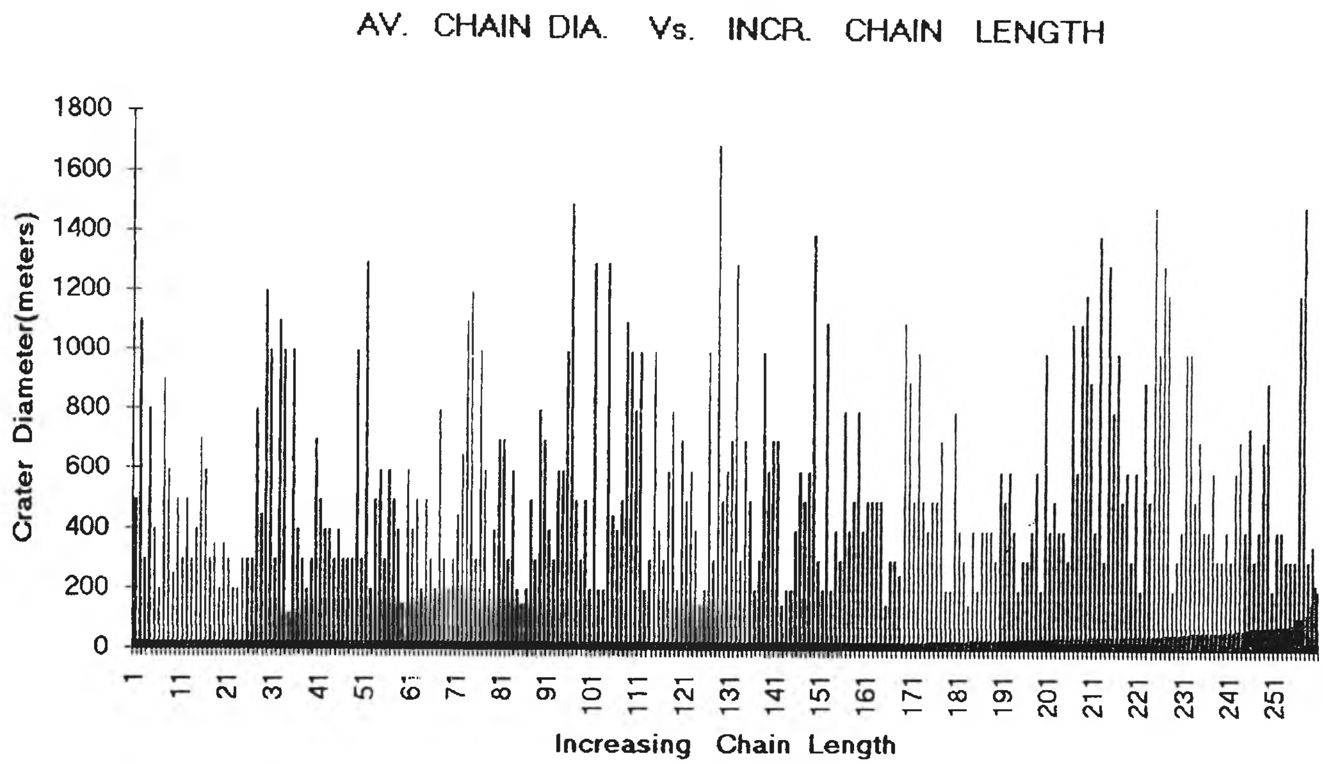
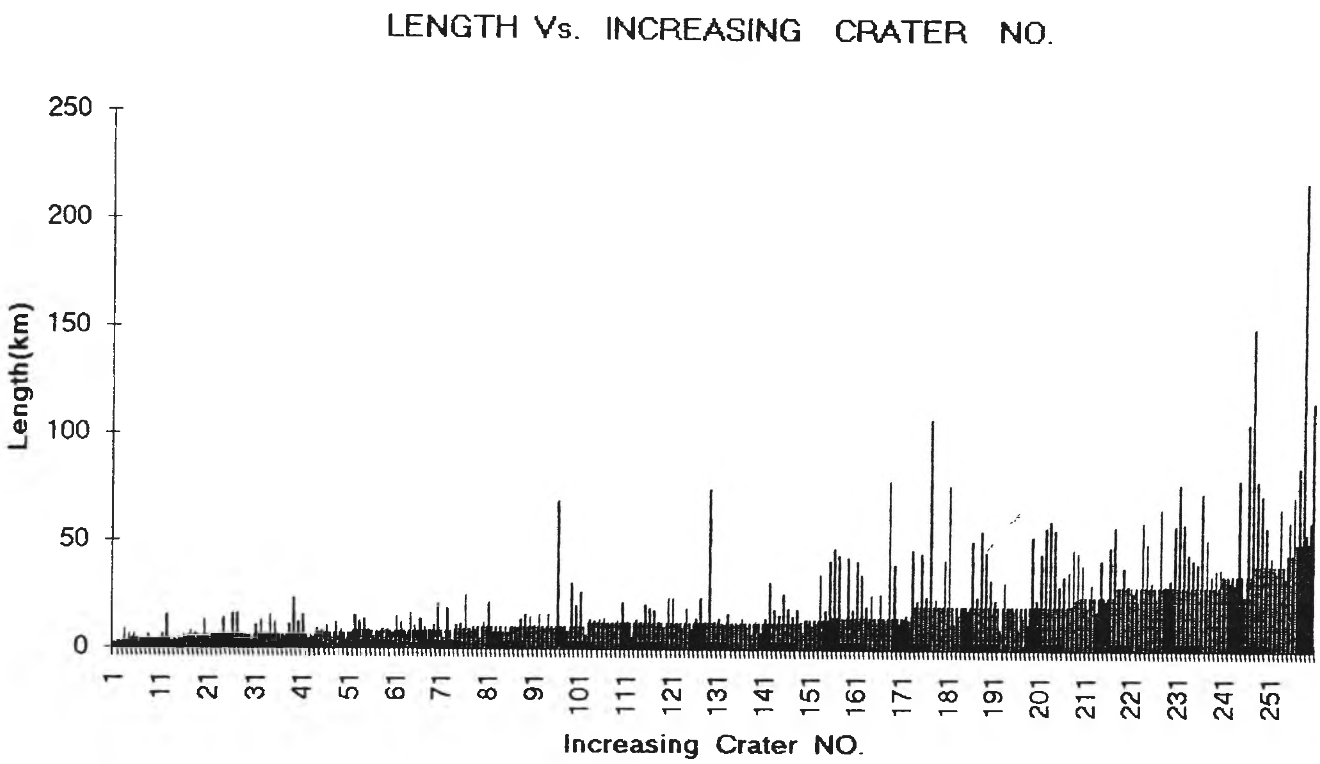

AV. CHAIN DIA. Vs. INCR. CHAIN LENGTH
Crater Diameter(meters)
0
200
400
600
800
1000
1200
1400
1600
1800
1
11
21
31
41
51
61
71
81
91
101
111
121
131
141
151
161
171
181
191
201
211
221
231
241
251
Increasing Chain Length

CHART 2



LENGTH Vs. INCREASING CRATER NO.
250
200
150
100
50
0
Length(km)
1
11
21
31
41
51
61
71
81
91
101
111
121
131
141
151
161
171
181
191
201
211
221
231
241
251
Increasing Crater NO.

CHART 3

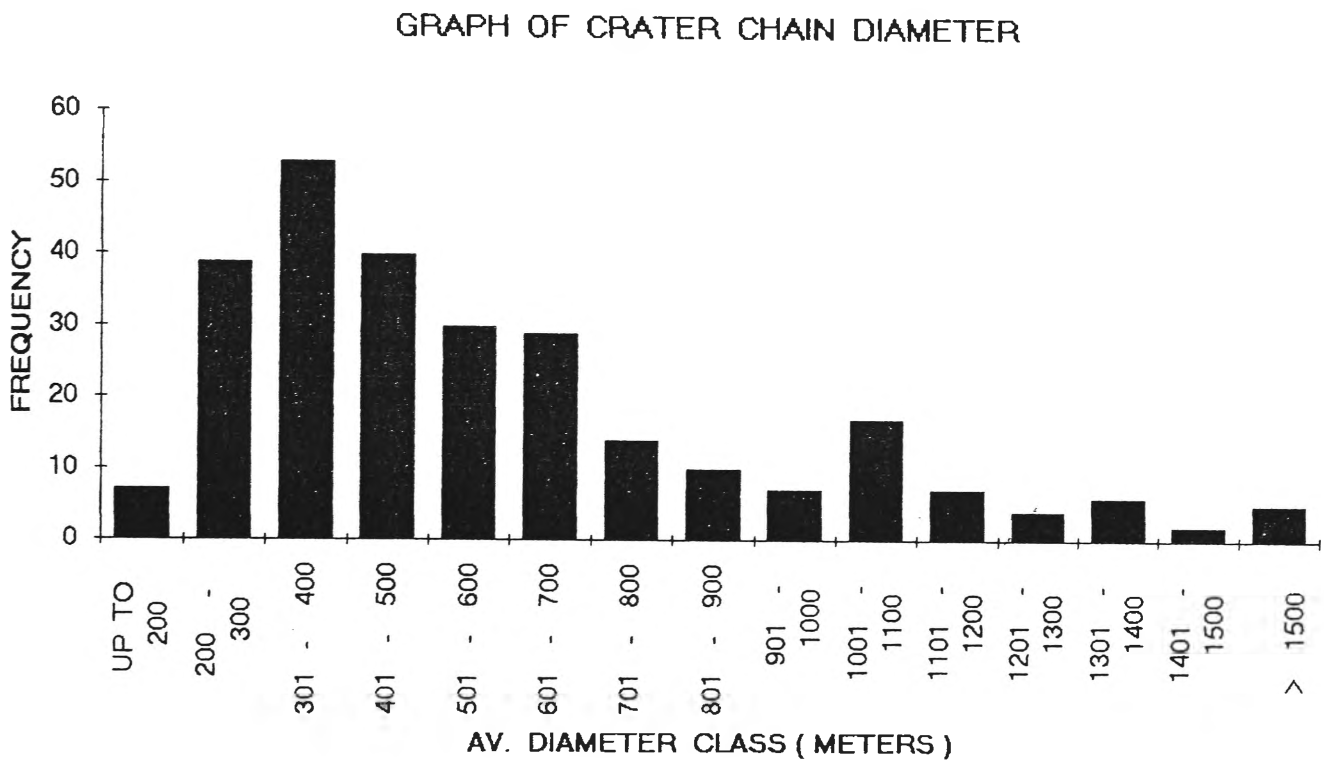
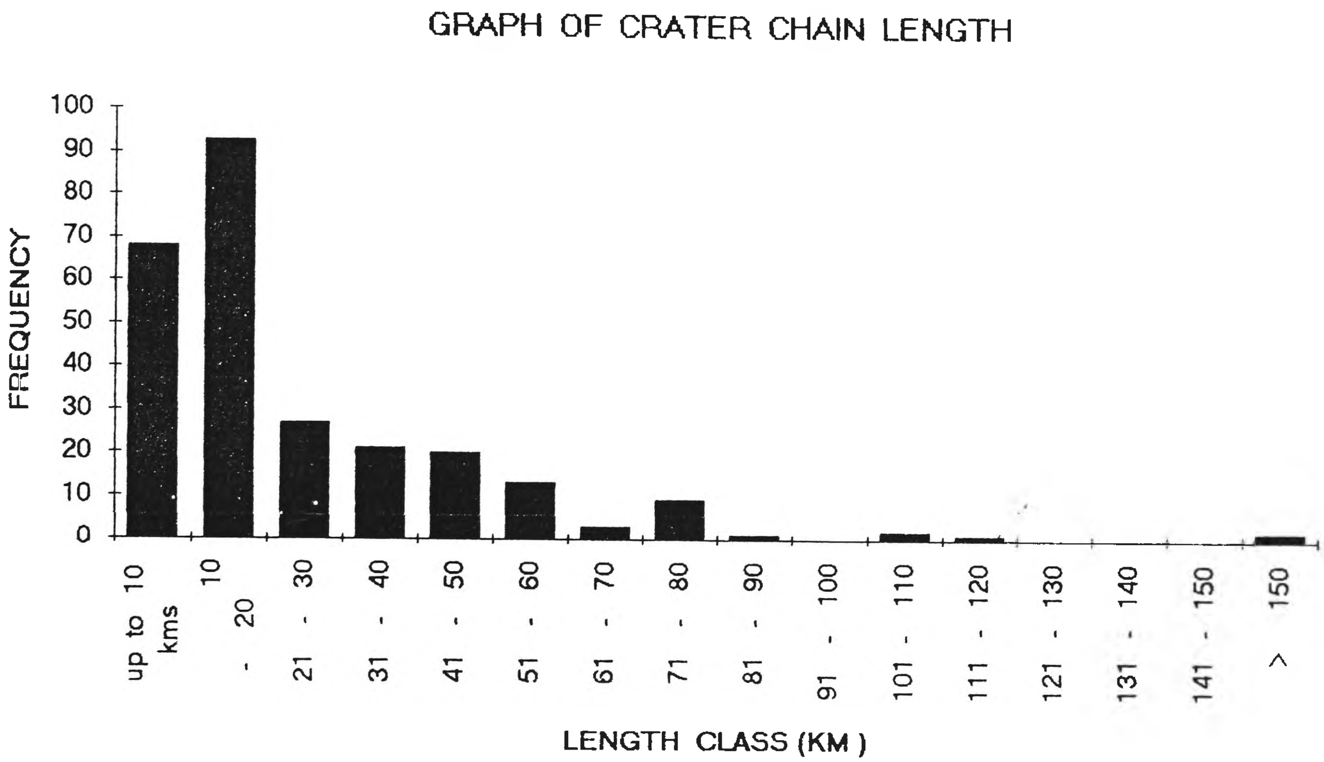

GRAPH OF CRATER CHAIN DIAMETER
FREQUENCY
60
50
40
30
20
10
0
UP TO 200
200 - 300
301 - 400
401 - 500
501 - 600
601 - 700
701 - 800
801 - 900
901 - 1000
1001 - 1100
1101 - 1200
1201 - 1300
1301 - 1400
1401 - 1500
> 1500
AV. DIAMETER CLASS (METERS)

CHART 4


GRAPH OF CRATER CHAIN LENGTH
FREQUENCY
100
90
80
70
60
50
40
30
20
10
0
up to 10 kms
10 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 100
101 - 110
111 - 120
121 - 130
131 - 140
141 - 150
> 150
LENGTH CLASS (KM)

APPENDIX B INDENTATION STATISTICS (Table 1)

NO.	LENGTH (kms)	WIDTH (kms)	SHAPE O-oval R-round E-elongated	Overlaid Faults (Yes\No)	Faults Overlaid (Yes\No)	Angle to Fault (90 is Perp) (0 is Parallel)	Shadow (Yes\No)	Old\Medium or Young (O\ M \ Y)
1	4.7	2.9	O	Y	N	90	N	M
2	3.1	0.9	E	N	N	0	Y	Y
3	1.5	1.2	R	Y	N	0	Y	M
4	8.7	1.7	E	N	N	-	N	Y
5	5.5	2.3	O	N	N	-	N	Y
6	8	2.3	E	N	N	-	N	Y
7	6.1	2.9	O	N	N	-	Y	Y
8	6.1	5	O	Y	N	0	N	M
9	12.8	2	E	Y	N	0	N	M
10	8.8	1.6	E	Y	N	0	N	M
11	86.6	8.5	E	N	N	-	Y	Y
12	7.7	2.6	O	-	-	-	N	O
13	6.8	2.7	O	-	-	-	Y	M
14	2.6	2.4	R	-	-	-	N	M
15	5.3	3.4	O	-	-	-	Y	M
16	2.8	1.3	O	-	-	-	N	M
17	3.8	2.6	O	-	-	0	N	M
18	5.3	2	E	Y	-	0	N	M
19	3.1	3	R	-	-	0	Y	M
20	2.9	3.1	R	-	-	0	N	M
21	8	1.1	E	-	-	0	Y	M
22	4.2	1.2	E	-	-	-	N	Y
23	9.7	1.6	E	Y	-	-	N	Y
24	8.9	2.1	E	Y	-	-	N	Y
25	14.6	1.9	E	Y	-	-	N	Y
26	17.2	2.3	E	Y	-	-	N	Y
27	6.6	1.7	E	Y	-	-	N	Y
28	85	6	E	-	-	-	Y	Y
29	47	3.6	E	-	-	-	Y	Y
30	37	6.6	E	-	-	-	Y	Y
31	13.1	2.6	E	-	-	-	N	M
32	4.9	2	E	-	-	-	N	M
33	5.1	1.4	E	-	-	-	N	M
34	13.1	2.2	E	-	-	-	Y	M
35	8.7	2.6	E	-	-	-	Y	M
36	13	3.3	E	-	-	-	N	M
37	4.3	5.2	R	-	-	-	Y	M
38	9.1	3.6	E	-	-	-	Y	M
39	8	2.7	E	-	-	-	Y	M
40	3.5	2.8	R	-	-	-	N	M
41	7.4	2.9	O	-	-	-	N	M
42	22	2.7	E	-	-	-	N	M
43	7.7	1.8	E	-	-	-	N	M
44	18.1	3.2	E	-	-	-	N	M
45	18.4	2	E	-	-	-	N	M
46	8.7	4.2	O	-	-	-	Y	M

47	13.1	1.1	E	-	-	-	N	M
48	5.8	5.1	R	-	-	-	N	M
49	6.8	6.2	R	-	-	-	N	M
50	4.8	2.3	O	-	-	-	N	M
51	2.9	2.8	R	-	-	-	N	M
52	26.2	11.7	E	-	-	-	Y	Y
53	20.6	7.5	E	-	-	-	Y	Y
54	10.5	5.1	E	-	-	-	Y	Y
55	9	5	O	-	-	-	Y	Y
56	6.7	3.8	O	-	-	-	Y	Y
57	8.1	1.7	E	-	-	-	N	Y
58	61.8	6	E	-	-	-	Y	Y
59	11.6	2.7	E	-	-	-	Y	Y
60	35.7	2	E	-	-	-	N	M
61	19.3	2	E	-	-	-	N	M
62	31	1.5	E	-	-	-	N	M
63	4.7	2.4	O	-	-	-	Y	Y
64	10	3	O	N	N	-	Y	M
65	3	1	O	N	N	-	N	M
66	15.5	5	E	N	N	-	Y	M
67	4.5	5	R	N	N	-	Y	M
68	30	1.7	E	Y	N	0	Y	M
69	60	3	E	N	N	-	N	M
70	45	6	E	N	N	-	Scalloped	M
71	37	1.5	E	Y	N	0	Y	M
72	47	1.5	E	Y	-	0	Y	M
73	13.4	2.4	E	-	-	-	Y	M
74	19	2	E	-	-	-	Y	M
75	7.3	3.8	O	-	-	-	Y	Y
76	24	3.6	E	Y	-	0	Y	Y
77	30	1.7	E	N	N	-	N	M
78	100	1.5	E	N	N	-	N	M
79	6.6	1.4	E	Y	-	0	Y	M
80	7.7	1.9	E	Y	-	0	Y	M
81	7.6	1.8	E	Y	-	0	Y	M
82	34.4	2.5	E	Y	-	0	Y	Y
83	1.3	1	O	Y	-	0	N	M
84	157	2.8	E	N	-	-	N	M
85	106.8	7.2	E	N	-	-	N	M
86	7.3	3	O	N	-	-	N	M
87	59	3	E	N	-	-	N	M
88	32	2.9	E	N	-	-	N	M
89	53	3.6	E	N	-	-	N	Y
90	4.2	0.9	E	N	-	-	Y	M
91	4.4	1.9	E	N	-	-	N	M
92	3.9	2.2	O	N	-	-	Y	M
93	14.6	6	E	N	-	-	N	M
94	58	4	E	N	-	-	N	M
95	8	4.7	O	N	-	-	N	M
96	7.4	1.4	E	N	-	-	N	M
97	36.6	2.3	E	N	-	-	N	O
98	5.1	1.3	E	N	-	-	N	M

99	12.8	1.4	E	Y	-	-	N	M
100	8.3	5.4	O	-	-	-	N	O
101	2	1.2	O	N	N	-	N	O
102	11.5	1.5	E	N	N	-	N	O
103	4.1	0.8	E	N	N	-	N	O
104	95	4.2	E	N	-	-	N	M
105	38	1.6	E	N	-	-	N	M
106	8.8	3.2	O	N	-	-	N	M
107	10.3	1.7	E	N	N	-	N	M
108	5.6	2.6	O	-	-	-	N	M
109	23	2.6	E	-	-	-	N	M
110	53	2	E	Y	-	0	N	M
111	21	3	E	N	-	0	N	M
112	19	6.2	O	-	-	-	N	M
113	16	4.2	E	-	-	-	N	M
114	11.9	2.4	E	Y	-	0	Y	O
115	51	5	E	Y	-	0	N	O
116	28	4.6	E	Y	-	0	N	O
117	27	3.6	E	Y	-	0	N	O
118	7.4	2.3	E	N	-	-	N	O
119	7.8	2.1	E	N	-	0	N	Y
120	5.3	2.6	E	N	-	0	N	Y
121	5	0.825	E	N	-	0	N	M
122	9.8	2	E	N	-	0	N	Y
123	2.4	2.4	C	N	-	-	N	Y
124	13.2	2.4	E	Y	-	0	N	M
125	27.2	0.4	E	N	-	-	N	M
126	27.6	7.7	O	N	Y	90	N	O
127	24.5	8	E	N	-	-	N	M
128	3.4	3	R	N	-	-	N	M
129	21	5	E	Y	-	-	N	M
130	1.9	1.9	R	-	-	-	N	M
131	22.8	1	E	N	-	-	N	O
132	17.2	2.9	E	N	-	-	N	M
133	44.8	3.3	E	N	-	90	N	O
134	21.8	2	E	Y	-	0	N	O
135	14.5	1.1	E	N	-	-	N	M
136	11.9	3.2	E	Y	-	0	N	O
137	8.4	8	R	N	-	0	N	O
138	20.9	3.3	E	N	-	0	N	M
139	15.6	1.7	E	N	-	0	N	O
140	307	2.6	E	N	-	-	N	M
141	5.5	3.1	O	N	N	-	N	M
142	4.2	3.4	O	N	N	-	N	M
143	21.8	11.6	O	N	N	-	N	M
144	20.5	1.7	E	N	N	-	N	Y
145	3	3.2	R	N	N	-	N	M
146	16.1	0.5	E	N	N	-	N	M
147	27.7	0.5	E	N	N	-	N	M
148	12.8	1.6	E	N	-	-	N	M
149	10.5	1.7	E	N	-	-	N	O
150	7.1	3.2	O	N	-	-	N	O

151	28	5.5	E	Y	-	0	N	O
152	4.8	2	O	N	-	90	N	O
153	8.3	0.6	E	N	-	90	N	O
154	32.9	4.6	E	N	-	-	N	O
155	8	4.1	O	Y	-	0	N	O
156	21.9	2.7	E	N	-	-	N	O
157	6	4	O	N	-	-	N	O
158	15	1.2	E	N	-	-	N	O
159	6.3	6	R	N	-	-	N	O
160	61.5	5.1	E	N	-	-	N	Y
161	29.4	4.2	E	N	-	-	N	Y
162	5.9	3.5	O	N	-	-	N	M
163	8.7	6	O	N	-	-	N	M
164	20.6	1.5	E	N	-	0	N	M
165	2.7	1.5	E	N	-	-	N	M
166	7.2	2.4	E	N	-	-	N	M
167	13.7	2.2	E	N	-	-	N	M
168	17.8	1.7	E	N	-	0	N	M
169	7.6	3.8	E	N	-	-	N	M
170	10	2.4	E	Y	-	0	Y	M
171	4.8	2.4	E	Y	-	0	N	M
172	3.7	1.2	E	N	-	-	Y	M
173	3.8	1.7	E	N	-	-	Y	M
174	2.7	1.2	E	-	-	-	Y	M
175	3.8	1.2	E	-	-	-	Y	M
176	7.3	2.4	O	-	-	-	N	M
177	23.6	1	E	-	-	-	N	O
178	23.7	1.7	E	-	-	-	Y	M
179	19.3	2.4	E	-	-	-	Y	M
180	7.8	1.9	E	Y	-	0	Y	Y
181	3.2	2.2	O	Y	-	0	Y	Y
182	9.8	5.4	E	-	-	-	N	M
183	93.6	4.5	E	-	-	-	N	O
184	7.3	6.1	R	-	-	-	N	M
185	9.3	2.6	E	-	-	-	N	O
186	10.9	4.7	E	-	-	90	N	M
187	16.9	10.6	O	-	-	90	N	M
188	6.8	2.9	O	-	-	-	N	Y
189	120	5.4	E	-	-	0	Y	M
190	48.8	2.6	E	-	-	90	N	M
191	33.5	1	E	-	-	-	N	M
192	6.5	3.5	O	-	-	-	Y	Y
193	3.7	3.4	R	-	-	-	N	Y
194	18	7.1	E	-	-	-	Y	Y
195	7.3	2.3	E	-	-	-	N	M
196	22.2	2.4	E	-	-	0	N	Y
197	72.3	2.9	E	-	-	0	N	Y
198	26.1	1.2	E	-	-	0	Y	Y
199	5.3	1.7	E	-	-	0	Y	Y
200	9.2	3.7	O	-	-	0	Y	Y
	Av=20.5	Av=3.1						
	1.3->307	0.4->11.7						

TABLE 2 INDENTATION LENGTH

CLASS LENGTH (kms)	FREQUENCY	CUMULATIVE FREQUENCY
Up to 10	105	105
10 - 20	36	141
21 - 30	26	167
31 - 40	10	177
41 - 50	5	182
51 - 60	6	188
61 - 70	2	190
71 - 80	1	191
81 - 90	2	193
91 - 100	3	196
> 100	4	200

TABLE 3 INDENTATION WIDTH

CLASS WIDTH (kms)	FREQUENCY	CUMULATIVE FREQUENCY
up to 1 km	7	7
1 - 2	64	71
2.1 - 3	58	129
3.1 - 4	26	155
4.1 - 5	16	171
5.1 - 6	14	185
6.1 - 7	4	189
7.1 - 8	6	195
8.1 - 9	2	197
9.1 - 10	0	197
10.1 - 11	1	198
11.1 - 12	2	200

CHART 1 INDENTATION WIDTH AND LENGTH

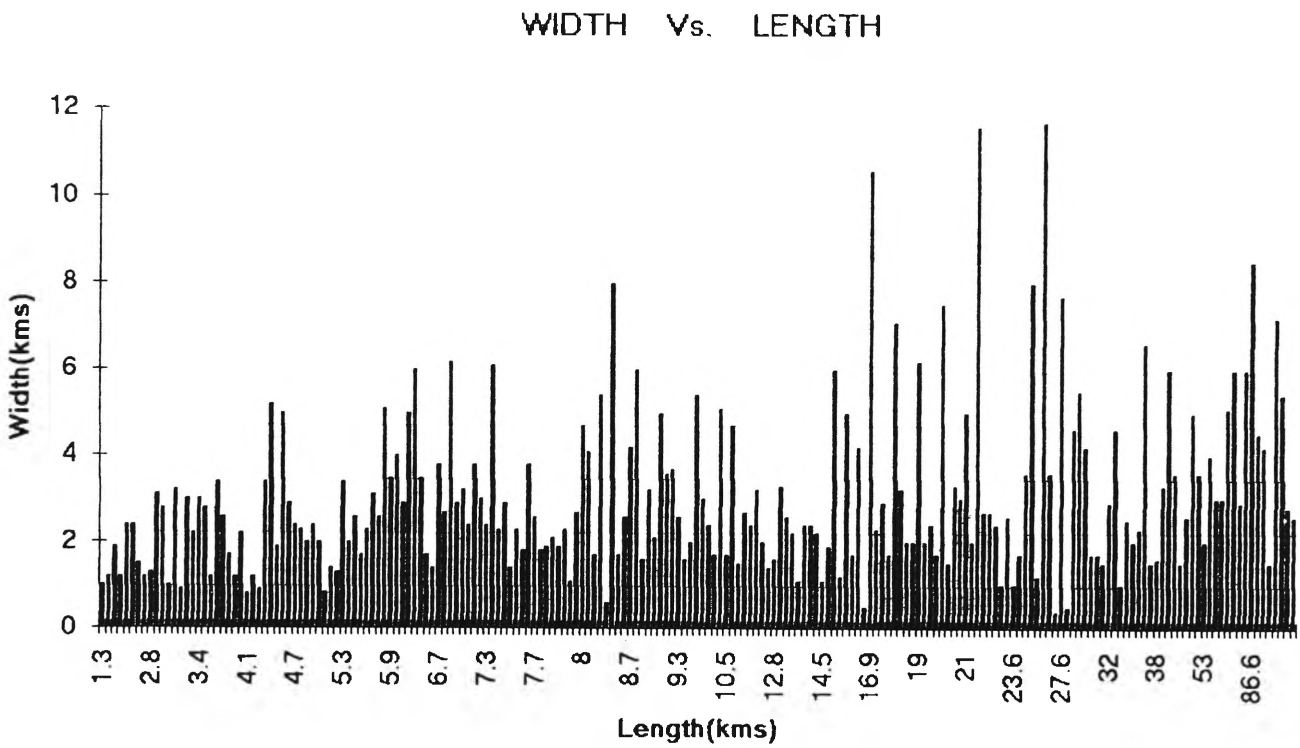


CHART 2 INDENTATION LENGTH

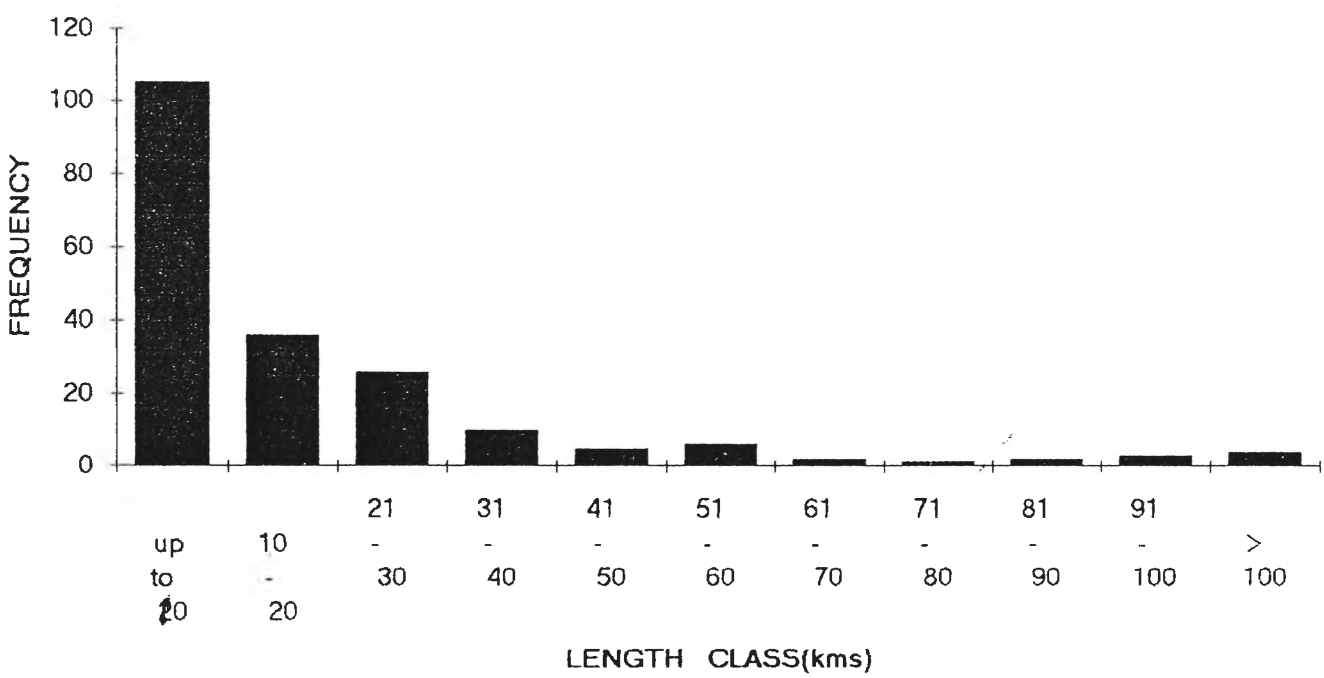
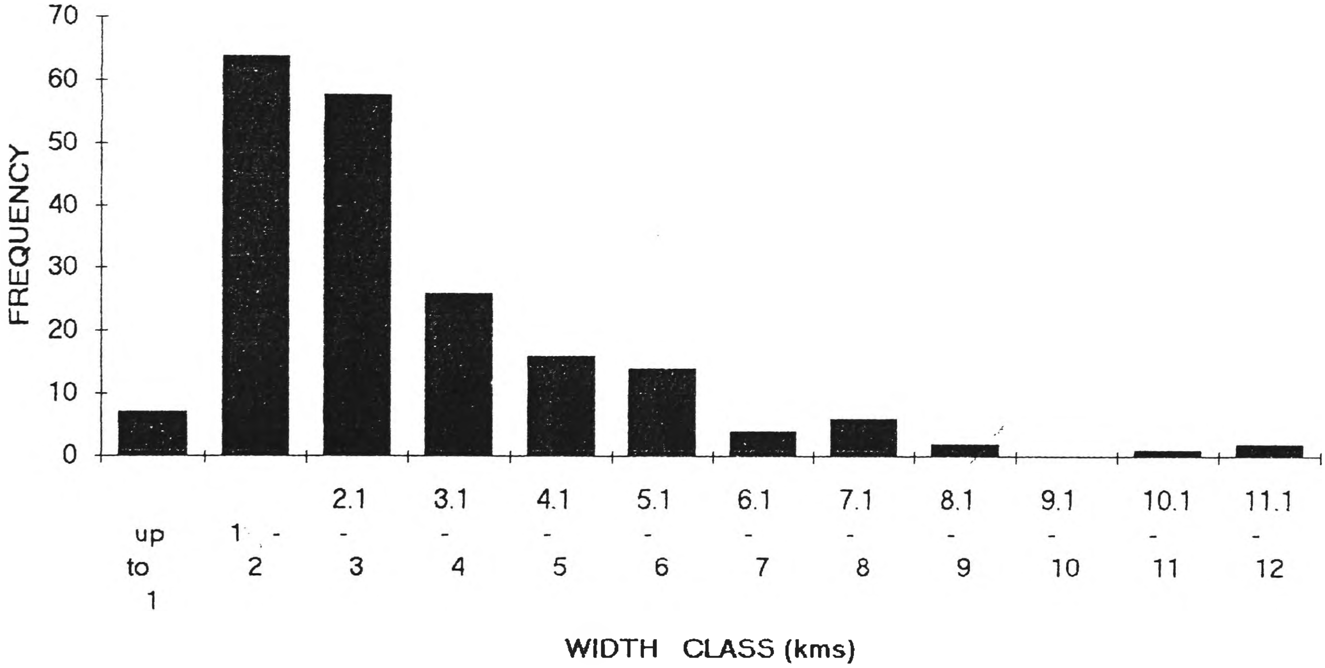


CHART 3 INDENTATION WIDTH



APPENDIX C

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Venus Unveiled: The Magellan Images

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Abstract: The availability of Magellan radar images of Venus on CDROM allows small research groups to engage in planetary physics projects using simple image processing systems. The material lends itself to short projects for high school students or Masters students.

Our initial investigations using the Magellan data have evolved into a Masters project which concentrates on the morphology of small scale structures which have terrestrial counterparts. These include studies of volcanic cone fields, lava tubes and other collapse features, and impact features.

1. Overview:

The planet Venus is similar in size to the Earth. Its surface experiences temperatures of up to 500°C and a pressure of 100 atmospheres. The surface of Venus is hidden beneath impenetrable cloud layers. It is therefore unclear whether the crust has evolved in a similar way to the Earth's crust. Early attempts at radar mapping utilised the Ariceibo and Goldstone radio telescopes and Pioneer Venus satellites. In 1983 the Soviet Venera missions obtained 1–2km resolution images of 25% of the surface. These observations revealed for the first time a surface showing considerable tectonic activity [folding, ridge belts, volcanism and coronae] as well as evidence for large impact craters.

In 1990 NASA's Magellan spacecraft began to orbit Venus and image its surface using a Synthetic Aperture Radar system. The initial mapping was completed in May 1991 and a second cycle in January 1992. The images allow objects a small as 80m across to be resolved.

The processed radar images are being released to researchers on 60 CDROMs. Each CDROM contains 10 fields [616 x 539 km] made up of 56 sub images. These images may be displayed and analysed using PC compatible computers using software developed by staff at the Jet Propulsion Laboratory.

The availability of such radar images allows small groups to engage in planetary physics projects at an early stage in the Magellan mission. The University of Wollongong Department of Physics is one of three groups in Australia working with these images.

2. The Aims of the Project

Many of the features observed on Venus are novel and appear unique to Venus. Since receiving the first CDROM in 1991, we have concentrated on identifying classes of structure which are directly comparable to terrestrial structures. We are currently studying the morphology of the following features:

(a) *Crater and cone fields*

Symmetrical volcanic cones are found in a variety of situations on Venus. Such features have also been described as "small domes" by Aubele and Slyuta (1990). In many cases they are associated with lava plains and large scale flow structures. These appear similar to the San Fransisco/ Navajo volcanics where some 175–200 individual cones have developed in the past 6Ma. Smaller cone fields are found associated with the summits of shield volcanoes and appear broadly similar to those found on Mauna Kea [Hawaii].

Using well tried analysis techniques we have begun a comparison of these cone fields with their terrestrial counterparts through studies involving :

- The distribution of cones and a comparison with underlying fault structures and graben. Such a study will use nearest neighbour techniques and rose diagrams to study the distributions.
- The assessment of the volume of material in each cone and lavas.
- The preparation of structural maps of flow units, identifying the age sequence.

Figure 1 shows a cone field on the flanks of Sif Mons. In this image smooth surfaces appear bright, while rougher surfaces appear dark. The lava flows associated with the complex cover a roughly circular area with a diameter of about 420 km. The main flow direction appears to be towards the west. To the SW the thin flows apparently overly the smooth, original, tessellated lavas.

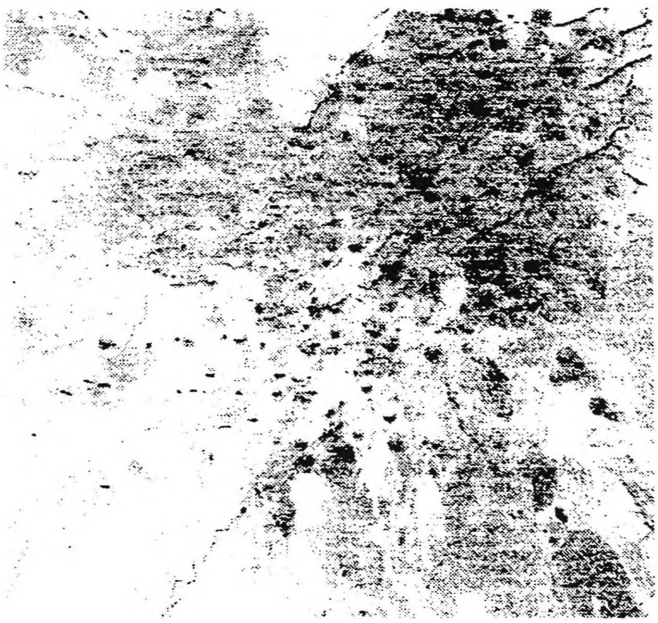


Figure 1: A cone field on the slopes of Sif Mons.

The cone density increases somewhat toward the centre of the region with cone diameters ranging from 2 km to 15 km. The distribution is somewhat elongated along a north–south axis, paralleling the major faulting which cuts through the central regions of the complex. There appear to be no chains of cones aligned with the main fault structures. There is a sharp cutoff in the cone distribution to the east.

The complex resembles a low shield volcano, on the flanks of Sif Mons. There are no clear rift features associated with the volcanics, although there is evidence of subsequent faulting. The major flow structures to the west appear to result from an underlying bowl-shaped topography opening in that direction.

(b) *Lava tubes and other drainage features*

Even a cursory study of the Magellan images reveals major complexes of connected collapse features similar to terrestrial lava tubes, but on a larger scale (Figure 2). Our initial study shows that these structures are generally associated with the upper slopes of volcanics and generally run down the slope. There appears to be a sequence of drainage features ranging from

- lines of small collapse/pit craters or maar which parallel faults
- connected scalloped craterlike features
- windowed lava tubes
- wide graben-like features running down slope

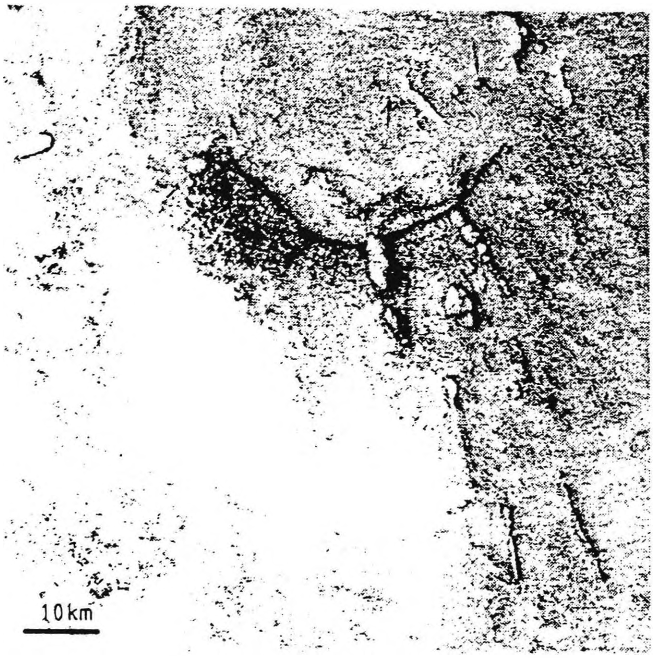


Figure 2: Chains of craters, open channels and indentations

In many cases a clear development from maar to graben is observed as one proceeds down slope. It is suggested that these features are the result of surface collapse after sub surface magma has withdrawn or flowed away. The possibility of explosive venting seems less likely considering the probable lack of surface and subsurface water.

One of the aims of this project is to compare such features with those on the Moon, Earth and Mars through measurement of their width, linearity, etc. Comparison of the variation of structure with the slope of the volcano may allow us to discuss the viscosity etc of the lava.

In this paper a lava channel is loosely referred to as any 'channel' or 'course' either on or below the surface which facilitates or has facilitated the flow of lava. There appear to be three types of structures directly related to the transfer of lava:

Crater Chains: These consist of chains of individual craters varying from 120 metres (the limit of resolution) to over a kilometre in diameter. The length of the chains are on average 20 kilometres but range from a few kilometres to 100 kilometres in length. Virtually all chains are perfectly straight and run parallel to the slopes and to other chains in their vicinity. They appear common on slopes associated with shield volcanics. The size of the craters grade from large to small as they proceed down slope.

Open Channels: These are long exposed channels which appear deep at their upper ends and merge with their surroundings at the lower. The average length of such a channel is 50km but some are over 200km in length. Many channels interconnect.

Typical widths, which vary along their length, are from 1 to 6km. Like the crater chains, they appear to widen closer to the summit of a slope.

The channels often have scalloped sides and run parallel to nearby crater chains and fault structures. Many have smooth edges and appear to be well worn, while others have a freshly formed appearance as evidenced by their sharp contours. A large percentage have dark floors indicating a smooth surface within. Open channels may be the Venusian counterpart of lunar rilles.

Indentations: These appear as long furrows which are normally closed at both ends. Although the most obvious features are long and narrow, shorter oval ones are not uncommon. Their lengths range from 2km to over 100km. Their widths are typically 2km although a few exceed 10km. The existence of radar shadowing indicates that many are deep. Sharp edges indicate some may be quite young and have suffered little gravitational slumping. Many appear to have been flooded with lava after their formation.

Indentations are as common as the crater chains but less common than open channels. Some do not seem to be associated with any visible volcanic activity.

Analysis

The observed features appear to be related to sub surface drainage of lava. This drainage may occur at depth and be controlled by fault structures, producing chains of pit craters as observed on the Kilauea rift zone in Hawaii. Alternatively surface contours may control the flow producing hollow lava tubes close to the surface. These lava tubes may then collapse leaving isolated oval windows or longer indentations as observed in some Queensland lava tubes (Stephenson and Griffin 1976). Some of the larger craters may represent collapses across the full width of the tube, whereas the smaller ones may be only partial collapses forming small windows in the tube roof.

The observed relation between the diameter of the features and altitude may result either from sub surface drainage or carrying a larger volume of lava close to the source resulting in a larger collapse feature.

Formation through explosive gas venting, while possible close to the source of magma are unlikely at any distance. This would need the lava to come into contact with a fluid such as water which is not thought to exist near the planet's surface.

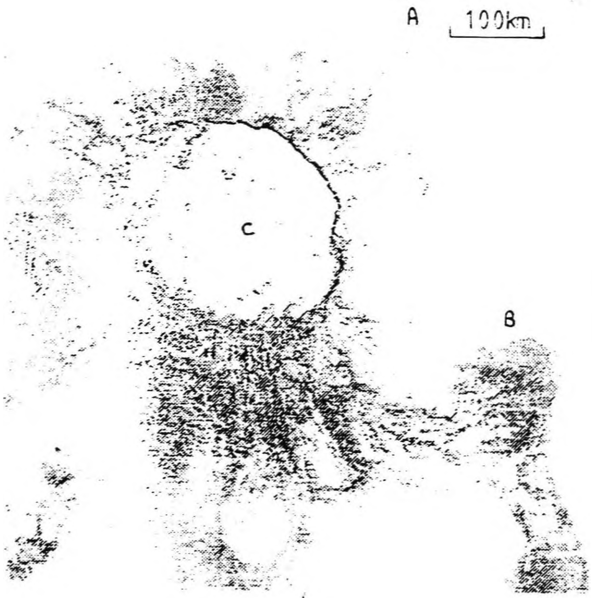
The open channels, crater chains and indentations have also undergone variable degradation due to their different ages which further complicate their study. This degradation may be due to gravitational slumping or chemical weathering.

Lava channels on Venus appear to be unique in their own right but have many features which have terrestrial and lunar counterparts. The features vary in scale from that similar to terrestrial lava tubes through to the scale of the much larger lunar rilles.

3: Impact craters

There are many large impact craters visible on the Magellan images. The diameters of these craters range from a few km to several hundred km. In most cases they are associated with an ejecta blanket which is lobate. This indicates that the ejecta has floated on some form of fluidised bed eg. a ground effect layer or vapourisation of ground fluids. The larger craters show the typical central rebound peak of impact structures and flat floors due to impact melting. Almost all craters are associated with secondary flow structures outside the crater rim. These appear similar to lava flows indicating that secondary volcanism may have been triggered by the impacts.

In the case of the largest impact structures, interesting flow structures may be observed within the crater itself. Figure 3 shows the concentric and radial patterns observed in the floor of a 150 km diameter crater. These appear similar to the pattern seen in convective cells in highly viscous fluids like bitumen. Could this impact have triggered a small shortlived convective plume?



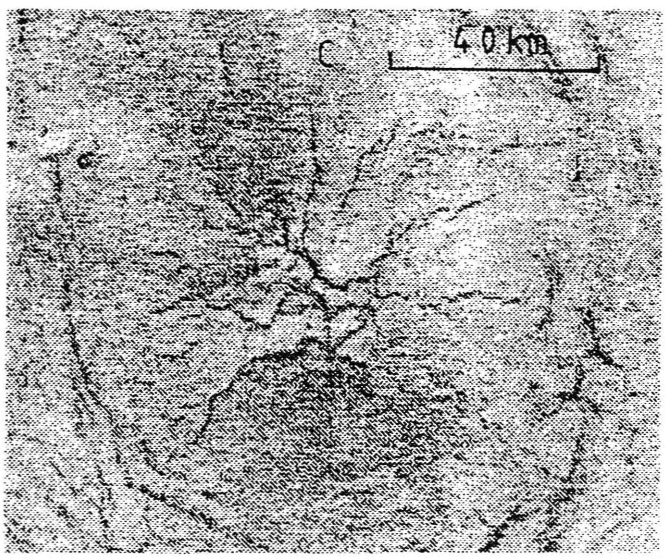


Figure 3: Chains of craters near the summit of Sif Mons

Perhaps the most surprising effect is the dark aureoles which surround most impact sites. These are thought to be due to a blast wave sweeping the surrounding terrain smooth immediately prior to impact. The footprint associated with these impacts may be as large as 100km by 500 km. This footprint often contains several impact craters, resulting from the incoming meteor breaking up in the atmosphere (figure 4).

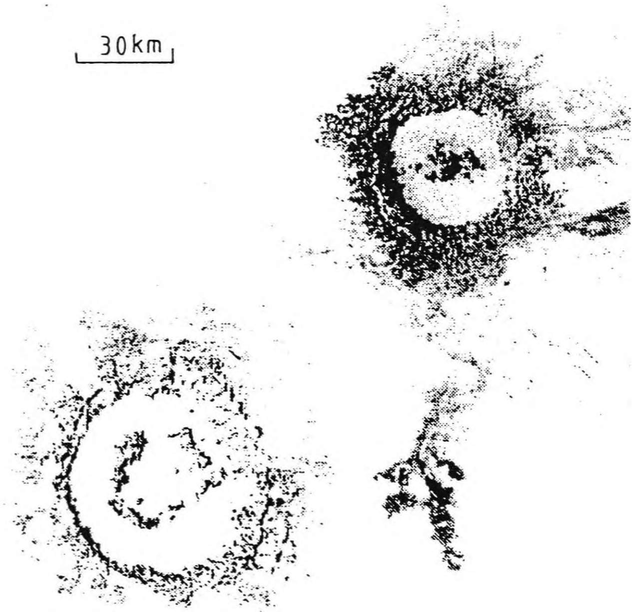


Figure 4: Secondary flow structures and crater floor convective flow in an impact crater

The geometry of the aureole can be used to estimate the direction and inclination of the incoming meteor. Some of the trails indicate grazing impacts at angles of less than 15° have formed craters with diameters less than 10 km. This is unexpected as simple mechanical considerations predict only large bodies will survive to reach the surface in such grazing impacts (Ivanov 1990).

The aims of this project are to

- categorise impacts structures according to diameter, presence of central peaks, multiple rims etc.
- estimate the inclination and direction of the paths of the impacting meteorites from their footprints and shape of the ejecta blanket.
- study the frequency of secondary volcanism associated with the impacts
- produce structural maps and identify age sequence of impacts, volcanics and underlying fault structures.
- model the impacts using simple laboratory simulations and computer models.

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